AFFTC-TR-98-26

# RESULTS OF ATTEMPTS TO PREVENT DEPARTURE AND/OR PILOT-INDUCED OSCILLATIONS (PIO) DUE TO ACTUATOR RATE LIMITING IN HIGHLY-AUGMENTED FIGHTER FLIGHT CONTROL SYSTEMS (HAVE FILTER)

AD INEXPLORATA

A F F T C

MICHAEL CHAPA
Captain, USAF
Project Manager

MARCH 1999

FINAL REPORT

Approved for public release; distribution is unlimited.

AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

This technical report (AFFTC-TR-98-26, *Results of Attempts to Prevent Departure and/or Pilot-Induced Oscillations (PIO) Due to Actuator Rate Limiting in Highly-Augmented Fighter Flight Control Systems [HAVE FILTER]*) was submitted under Job Order Number M96J0200 by the Commandant, USAF Test Pilot School, Edwards Air Force Base, California 93524-6485.

Prepared by:

MICHAEL CHAPA
Captain, USAF
Project Manager

MATTHEW LETOURNEAU
Lieutenant Commander, USN
Project Pilot

TERRY PARKER
Flight Lieutenant, RAF
Project Pilot

ERIC FICK
Captain, USAF
Flight Test Engineer

DARREN KRAABEL
Captain, USAF
Flight Test Engineer

This test report has been reviewed and is approved for publication: 23 March 1999

ERNIE H. HAENDSCHKE
Lt Col, USAF
Commandant, USAF Test Pilot School

ROGER C. CRANE
Senior Technical Advisor
412th Test Wing

GARALD K. ROBINSON
Colonel, USAF
Commander, 412th Test Wing

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



| 1. AGENCY USE ONLY (Leave blank) | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | March 1999 | 1 to 18 September 1998 |

**4. TITLE AND SUBTITLE**
Results of Attempts to Prevent Departure and/or Pilot-Induced Oscillations (PIO) Due to Actuator Rate Limiting in Highly-Augmented Fighter Flight Control Systems

**5. FUNDING NUMBERS**
JON: M96J0200
PEC: 65807F

**6. AUTHOR(S)**
Chapa, Michael, Capt, USAF
Fick, Eric, Capt, USAF
Kraabel, Darren, Capt, USAF
Letourneau, Matthew, Lt Comm, USN
Parker, Terry, Flight Lt, RAF

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES**
AFFTC
USAF Test Pilot School/EDT
220 S Wolfe Ave
Edwards AFB CA 93524-6485

**8. PERFORMING ORGANIZATION REPORT NUMBER**
AFFTC-TR-98-26

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Air Force Research Laboratory, AFRL/VAAI
2210 8th Street Suite 20
Bldg 146 Room 301
Wright-Patterson AFB OH 45433

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
N/A

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution is unlimited.

**12b. DISTRIBUTION CODE**
A

**13. ABSTRACT** *(Maximum 200 words)*

The objective of this effort was to evaluate the effects of software rate limiting the pilot command with and without a software pre-filter on a highly-augmented fighter aircraft flight control system. The software rate limiter and software pre-filter were designed to provide protection from departure and/or pilot-induced oscillation (PIO).

In statically unstable aircraft stabilized with feedback, elevator/stabilator actuator rate limiting may lead to PIOs and/or departure during aggressive maneuvers. This project examined the use of a software rate limiter (SWRL) on the pilot command and compared the results with those for the unprotected airframe. Additionally, a nonlinear rate limiter pre-filter (RLPF) was used in conjunction with the SWRL. Previous attempts to suppress PIO and/or departure tendencies using similar technologies have encountered difficulty with noise-in-the-loop and out-of-trim bias development during filter operation. This project attempted to improve previous designs using a different algorithm for the RLPF.

The SWRL was found to help prevent PIO and/or departure. The RLPF plus SWRL was generally found to be more helpful than the SWRL alone at preventing PIO and/or departure. However, handling qualities deficiencies arose when using low SWRL settings and worsened with low SWRL settings used in conjunction with the RLPF.

**14. SUBJECT TERMS**
pilot-induced oscillation
software rate limiting
static instability
handling qualities
departure susceptibility
rate limiting

**15. NUMBER OF PAGES**
80

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | SAR |

This page intentionally left blank.

# PREFACE

This technical report presents the evaluation procedures, concept, and results from the completion of the HAVE FILTER test project. The objective of this effort was to evaluate the effects of software rate limiting on the pilot command with and without a software pre-filter on a highly-augmented fighter aircraft flight control system. The software rate limiter and software pre-filter were designed to provide protection from departure and/or pilot-induced oscillation.

Descriptions of the HAVE FILTER system, test support equipment, instrumentation, test methods, and test procedures are provided within this document as a prelude to test results presentation. Thirteen test flights were conducted by the USAF Test Pilot School (TPS) HAVE FILTER test team at the Calspan flight research facility in Buffalo, New York, from 1 through 18 September 1998, accumulating 14.9 hours of flying time. The project was sponsored by the Air Force Research Laboratory, Wright-Patterson AFB, Ohio, and supported by the USAF TPS and the Air Force Institute of Technology as part of both schools' curricula.

This page intentionally left blank.

# FROM THE COMMANDER

I am pleased to report on the results of the evaluation procedures, concept, and results of the HAVE FILTER flight test project. The objective of this effort was to evaluate the effects of software rate limiting the pilot command with and without a software pre-filter on a highly-augmented fighter aircraft flight control system. The software rate limiter and software pre-filter were designed to provide protection from departure and/or pilot-induced oscillation (PIO). Evaluations were compared to the same aircraft without protection.

Tests were conducted 1 through 18 September 1998, by the USAF Test Pilot School (TPS) HAVE FILTER test team at the Calspan flight research facility in Buffalo, New York. Thirteen flights (four calibration/validation and nine test flights) totaling 14.9 flight hours were completed. The project was sponsored by the Air Force Research Laboratory and supported by the USAF TPS and the Air Force Institute of Technology (AFIT) as part of both schools' curricula. Work was conducted under Air Force Flight Test Center Job Order Number M96J0200.

In statically unstable aircraft stabilized with feedback, elevator/stabilator actuator rate limiting may lead to PIOs and/or departure during aggressive maneuvers. This project examined the use of a software rate limiter (SWRL) on the pilot command and compared the results with those for the unprotected airframe.

Additionally, a nonlinear rate limiter pre-filter (RLPF) was used in conjunction with the SWRL. Previous attempts to suppress PIO and/or departure tendencies using similar technologies have encountered difficulty with noise-in-the-loop and out-of-trim bias development during filter operation. This project attempted to improve previous designs using a different algorithm for the RLPF.

The SWRL was found to help prevent PIO and/or departure. The RLPF plus SWRL was generally found to be more helpful than the SWRL alone at preventing PIO and/or departure. However, handling qualities deficiencies sometimes arose when using low SWRL settings and worsened with low SWRL settings used in conjunction with the RLPF.

Garald K. Robinson

GARALD K. ROBINSON
Colonel, USAF
Commander, 412th Test Wing

This page intentionally left blank.

# TABLE OF CONTENTS

Page No.

## LIST OF ILLUSTRATIONS

## LIST OF ILLUSTRATIONS (Concluded)



## LIST OF TABLES

This page intentionally left blank.

# INTRODUCTION

## GENERAL

Pilot-induced oscillations (PIOs) and/or departure suppression filters were tested on the NF-16D Variable Stability In-Flight Simulator Test Aircraft (VISTA). Testing was performed at the Calspan flight research facility in Buffalo, New York, by a team of USAF Test Pilot School (USAF TPS) students. Thirteen test flights were flown 1 through 18 September 1998, accumulating 14.9 hours of flying time.

This test program was sponsored by Air Force Research Laboratory (AFRL), Wright-Patterson AFB, Ohio, as part of a Master's thesis through the joint Air Force Institute of Technology (AFIT)/USAF TPS program. Work was accomplished under Job Order Number M96J0200. The responsible test organization (RTO) was the Air Force Research Laboratory, Wright-Patterson AFB, Ohio. The USAF TPS test team was the participating test organization (PTO). Four calibration/validation flights and nine test flights were flown in support of this project.

This project was conducted under the authority of the Commandant, USAF TPS and sponsored by the AFRL. Additional guidance on technical requirements was given by the AFIT.

## BACKGROUND

This project was part of the joint AFIT/TPS program. The flight test portion was a follow-on to an AFIT Master's Thesis titled *A Nonlinear Pre-Filter to Prevent Pilot-Induced Oscillations Due to Rate Limiting* (Reference 1). Actuator rate limiting has been identified as a leading nonlinear cause of PIO. Since increasing actuator rates may not always be possible due to cost and/or weight, some rate limiting is expected during high bandwidth pilot-in-the-loop tasks. Extreme rate limiting inducing excessive phase lag (or time delay) in the flight control loop may exceed stability margins. An interesting case exists with highly-augmented fighter aircraft (HAFA) where the bare aircraft dynamics are unstable. During rate limiting, the response tends back to unstable unaugmented dynamics. Theoretically, intentionally software rate limiting the pilot command may prevent instability.

However, intentionally software rate limiting the pilot can add undesirable phase lag into the loop. Attempts have been made to eliminate and/or minimize phase lag due to rate limiting by use of a pre-filter. Some of these attempts encountered difficulty with noise-in-the-loop and out-of-trim bias development during filter operation (Reference 2). This project improved previous designs using a different algorithm for the nonlinear rate limiter pre-filter (RLPF). This project examined using a software rate limiter (SWRL) on the pilot command with and without the RLPF to compare with the unprotected airframe.

### <u>Test Overview:</u>

The HAVE FILTER test program used the VISTA NF-16D aircraft to simulate two highly-augmented fighter aircraft with identical unstable inner loops. When not under rate limiting conditions, the feedbacks resulted in two different sets of aircraft dynamics. Using MIL-STD 1797A (Reference 3) control anticipation parameter (CAP) criteria, one of these (HAFA 1) was predicted to have level 1 handling qualities. The other, HAFA 2, was predicted to have level 3 handling qualities.

The SWRL and RLPF performances were evaluated using a buildup approach. Phase 1 (semi-closed loop handling qualities) tasks were followed by phase 2 (high bandwidth handling qualities during tracking [HQDT]) using a pitch axis head-up display (HUD) tracking task. These maneuvers were followed by a phase 3 (operational tracking) task. During the phase 3 task, the pilot attempted to track a multi-axis maneuvering HUD target, minimizing error throughout the task. Although during phase 3 the HUD target moved in both the pitch and roll axes, the primary emphasis of this project was pitch tracking.

Comparisons between the baseline aircraft, the baseline plus SWRL, and the baseline plus RLPF plus SWRL combination were made. Critical data included pilot comments, PIO tendency ratings for the phase 2 and 3 tasks, and Cooper-Harper ratings (CHRs) for the phase 3 task.

## Related Tests and Simulation:

In support of the current project, MATLAB™ and SIMULINK™ simulations were accomplished as well as testing in the Large Amplitude Multimode Aerospace Simulator (LAMARS) at Wright-Patterson AFB, Ohio, during October and November 1997 (Reference 1). The HAVE LIMITS (Reference 4) test program demonstrated the effects of rate limiting during a pitch tracking task on a highly-augmented aircraft.

MATLAB™ and SIMULINK™ simulations were also completed to optimize the tracking task gain. An optimized tracking task was one that had large enough pitch changes to cause departure on the baseline aircraft configurations at some point in the profile without causing nuisance safety trips. Time histories of stabilator command, angle of attack, pitch rate, normal acceleration, angle-of-attack rate, and pitch angle were recorded during the tracking task using a modified Neal-Smith pilot model (Reference 3). All three test configurations for the HAFA 1 aircraft were simulated using various software rate limits and pre-filter acceleration thresholds.

# TEST ITEM DESCRIPTION

The test item for the HAVE FILTER test program consisted of several components implemented into the VISTA Variable Stability System (VSS): unstable bare airframe dynamics (pole at s=+1.34 with a time to double amplitude, $T_2$, of 0.5 second), pitch rate and angle-of-attack feedbacks generating the HAFA 1 and HAFA 2 overall dynamics (Appendix A), the SWRL software as implemented into the VSS, the RLPF as implemented into the VSS, and the stick dynamics. The VISTA NF-16D stabilator actuators were software rate limited to 60 degrees per second inside the feedback loop to simulate typical modern fighter aircraft and keep the VISTA from rate limiting. The VISTA's actual actuator rate limit was 70 degrees per second at the test condition. The SWRL was simply an additional software selectable rate limiter placed on the pilot command (outside the feedback loop) to protect the 60 degrees per second actuator from rate limiting. The RLPF algorithm was placed in front of the SWRL and had a software selectable stick acceleration threshold setting. The RLPF attempted to minimize and/or remove any phase lag introduced by the SWRL and command bias removal after filter operation. Refer to Figures A5 through A8 for flight control diagrams of the baseline, baseline plus SWRL, baseline plus RLPF plus SWRL, and RLPF logic.

# TEST AIRCRAFT

The test aircraft, the VISTA USAF NF-16D SN 86-0048, was owned by the AFRL and operated and maintained by Calspan. The VISTA was a highly-modified Block 30 Peace Marble F-16D aircraft with Block 40 avionics powered by an F100-PW-229 engine. The front cockpit included several VSS control panels, a removable variable feel centerstick controller, and a variable feel sidestick controller. The sidestick controller had a rotation angle of 10.5 degrees and stick gains of 20.0 and 5.7 degrees of stabilator command per inch of stick deflection for the HAFA 1 and HAFA 2 configurations, respectively. The sidestick properties are shown in Table 1.

Table 1
SIDESTICK CHARACTERISTICS

| | Pitch | Roll |
|---|---|---|
| Gradient | 51 pounds/inch (lb/in) | 21 lb/in |
| Fwd/Left | -0.35 inches (in) | -0.55 in |
| Aft/Right | +0.75 in | +0.55 in |
| Natural Frequency, $\omega_n$ | 30 radians/second (rad/sec) | 30 rad/sec |
| Damping Ratio, $\zeta$ | 0.7 | 0.7 |

The front cockpit also included a programmable display system (PDS) for the HUD. Most basic aircraft switches and controls were moved to the rear cockpit for the safety pilot. The rear cockpit used conventional F-16 controls except that the throttle was driven by a servo system when VSS was in use. The primary VSS controls and displays were also located in the rear cockpit. The hydraulic system was enhanced with increased capacity pumps, lines, and high-rate actuators for the flaperons and horizontal tails.

The analog flight controls system was replaced with a modified Block 40 Digital Flight Control System which incorporated the interface for the VSS. The VSS generated signals to operate the flight controls using a virtually unlimited set of command gains that were changeable in flight. The system consisted of three Hawk computers that generated the commands for the flight controls, a feel system computer controlled the feel for the front cockpit sidestick, and a Raymond disk that stored preprogrammed sets of gains and control laws for VSS operation. More detailed information can be found in the *NF-16D 86-0048 Partial Flight Manual* (Reference 5). The VISTA operational envelope is shown in Figure 1.

Two different aircraft configurations were required for completion of this test project. The effects of the test item on both HAFA 1 and HAFA 2 aircraft configurations were evaluated. Descriptions of those configurations are contained in Appendix A.

## TEST OBJECTIVE

The test objective was to evaluate the performance of a software rate limit and nonlinear RLPF on the pilot command of a highly-augmented fighter aircraft under actuator rate limiting during a fighter HUD tracking task. Both HAFA 1 and HAFA 2 aircraft configurations were flown. The test objective was met.

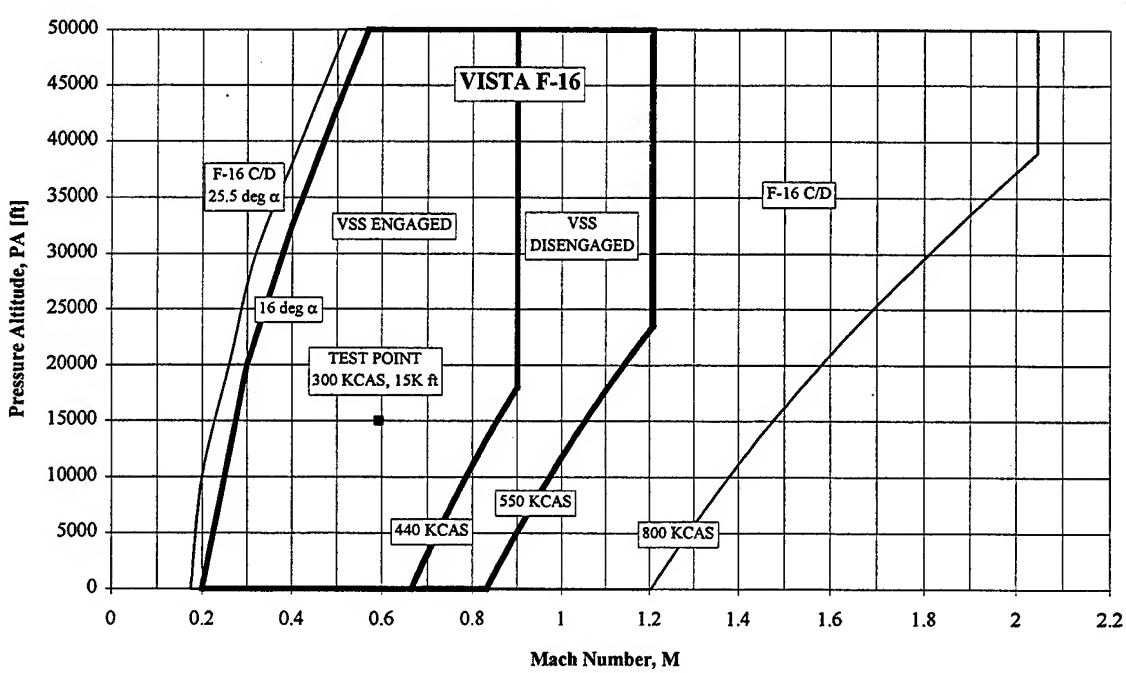


Figure 1 Variable Stability In-Flight Simulator Test Aircraft Operational Envelope, 1 g

### HAFA 1 and HAFA 2 Handling Qualities (Configuration A):

Determined baseline handling qualities for the HAFA 1 and HAFA 2 aircraft described in Appendix A.

### Software Rate Limiter Evaluation (Configuration B):

Evaluated the protection provided by a software rate limiter acting on the pilot command. Compared results to the baseline airframe handling qualities for both the HAFA 1 and HAFA 2 aircraft.

### Rate Limiter Pre-Filter plus SWRL Evaluation (Configuration C):

Evaluated the performance of the rate limiter pre-filter plus software rate limit (RLPF plus SWRL) on the pilot command. Compare results to the baseline airframe and baseline airframe plus SWRL handling qualities for both the HAFA 1 and HAFA 2 aircraft.

## LIMITATIONS

The primary limitation on this project stemmed from VISTA safety trips. As previously discussed, the VISTA test aircraft was equipped with over 100 safety trips to prevent the pilot from putting the aircraft in an unrecoverable position and protect against structural damage. Since one of the primary data points in this investigation was departure susceptibility, the test aircraft was routinely driven to one or more of those limits. Occasionally, nuisance safety trips resulted in incomplete tasks and inconclusive departure susceptibility data. Those points were labeled as inconclusive throughout the report.

# TEST AND EVALUATION

## GENERAL

This project evaluated the effectiveness of a SWRL with and without an RLPF to prevent departure and/or PIO during a HUD tracking task on a highly-augmented fighter aircraft. Lateral and directional handling qualities were not evaluated, but the roll task was included because the customer theorized that including a roll task would better unveil pitch problems. A total of 13 sorties were flown in support of this project: 4 calibration/validation sorties and 9 test sorties. Flights were conducted at the Calspan flight research facility in Buffalo, New York, from 1 through 18 September 1998. The flight test programmable HUD tracking technique[1] was used on the VISTA NF-16D aircraft.

All testing was conducted at 15,000 feet pressure altitude and 300 knots calibrated airspeed (KCAS). Three configurations were tested on both HAFA 1 and HAFA 2:

1. Baseline aircraft,

2. Baseline aircraft with the addition of a SWRL, and

3. Baseline aircraft with the RLPF plus SWRL combination.

These configurations are described in Appendix A. Five SWRL settings were explored, both with (configuration C) and without (configuration B) the RLPF algorithm, which was evaluated at a single stick acceleration setting only.

Each pilot flew the same test points but was blind to the configuration selection throughout the flight test phase of the project. However, the safety pilot knew which test points were being flown and implemented configuration changes in flight. Pilots are identified throughout the report as described in Table 2.

Ground testing was accomplished by the contractor prior to the calibration and test flights. Ground testing verified proper implementation of the test matrix and proper operation of the VSS system and HUD tracking tasks.

## TEST PROCEDURES

### Head-Up Display Tracking Task Techniques:

A flight test programmable HUD tracking technique was used. Two different HUD tracking profiles were used, both of which were based on tasks contained in MIL-STD 1797A (Reference 3). These tracking tasks were truncated in time based on simulation results and limited available flight time. The HUD tracking task No. 1 (Figure 2) was used for the phase 2 high bandwidth HQDT portion of each test point. The HUD tracking task No. 1 was a pitch maneuvering profile only.

For the calibration flights and the first data flight, the HQDT task was flown as shown in Figure 2 (hereafter referred to as the large amplitude HQDT task). Nuisance safety trips presented a problem at this amplitude, thus the HQDT task was reduced to one-fourth of that shown in Figure 2 for the remainder of flight test.

[1] The MIL-STD-1797A recommended HUD tracking techniques (Reference 3).

Table 2
PILOT DESIGNATIONS

| Pilot | Designation | Primary Operational Experience | Total Flight Hours |
|---|---|---|---|
| Michael Chapa, Capt, USAF | Pilot A | F-15/F-16 | 1,350+ |
| Matthew LeTourneau, Lt Cmdr, USN | Pilot B | F-14 | 1,500+ |
| Terry Parker, Flt Lt, RAF | Pilot C | AV-8 | 2,000+ |

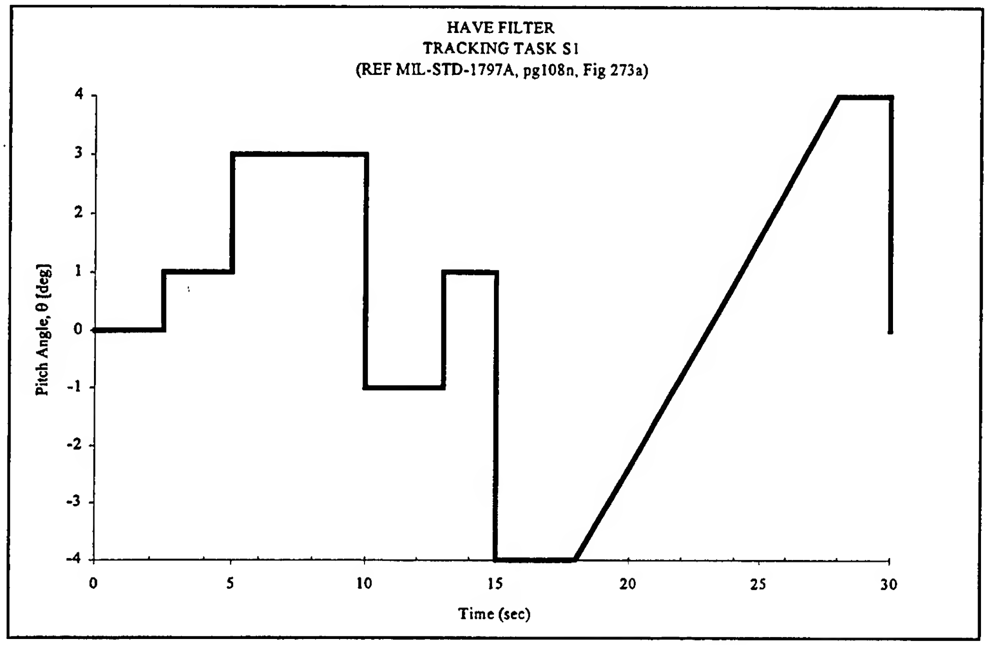


Figure 2 Head-Up Display Tracking Task No. 1

The HUD tracking task No. 2 (Figures 3 and 4) was used during phase 3 and contained both pitch and roll motion. The pitch-axis tracking task amplitude was doubled for all test points (simulation predicted 150 percent of task in Figure 3 would be needed to ensure desirable departure characteristics). The roll-axis tracking task was flown as depicted or its mirror image for a given test point. The roll-axis task was identical for each evaluation pilot at a given data point. The purpose in varying the roll-axis task was to minimize anticipation. The pitch tracking task shown in Figure 3 was implemented in such a manner as to always command a rotation about the y-axis of the aircraft in its x-z plane, not necessarily a change in pitch angle, theta, as shown. As such, when the tracking task commanded a 3-degree pitch angle, the programmable HUD commanded a 3-degree rotation about the aircraft y-axis.

As previously discussed, the VISTA test aircraft was equipped with over 100 safety trips to prevent the pilot from putting the aircraft in an unrecoverable position and/or preventing structural damage. Since one of the primary data points was departure susceptibility, the test aircraft was routinely driven to one or more of those limits. After 6 of 9 data flights, Calspan determined they could remove several nuisance derived safety trips[2] without concern for safety and/or damage to the aircraft. After these trips were removed, approximately 75 percent of the nuisance safety trips disappeared. However, pilot observations during flight, postflight evaluations of

[2] The three safety trips removed were titled pdot_diff, qdot_diff, and rdot_diff. These safety trips were activated when differences between two angular acceleration calculations rose above a set level. These calculations determined angular accelerations (roll, pitch, and yaw accelerations) using linear accelerometers and involved extremely dirty data signals.

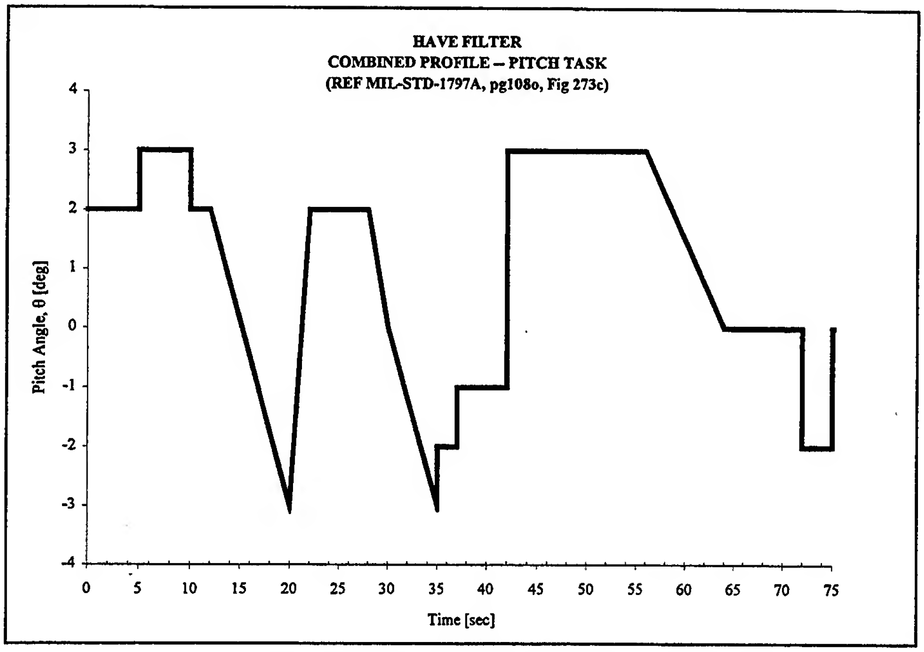


Figure 3 Head-Up Display Tracking Task No. 2, Pitch Axis

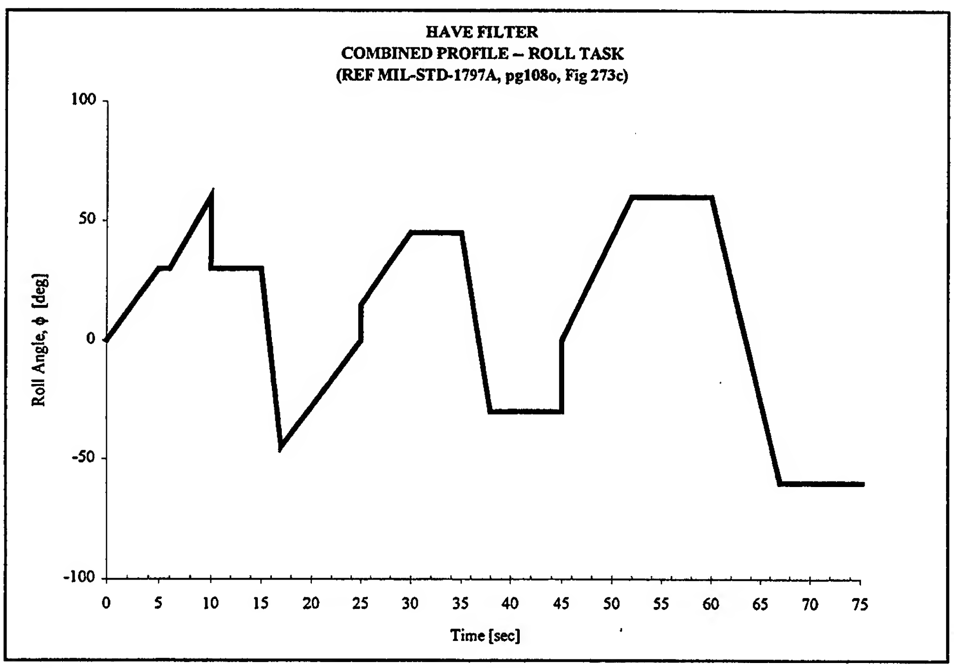


Figure 4 Head-Up Display Tracking Task No. 2, Roll Axis

the HUD video, safety trip information, and data traces were not always definitive in determining whether the aircraft was departing when a safety trip occurred. These points resulted in an incomplete task, unclear results, and were labeled as inconclusive. **To save valuable flight test time and resources, remove unnecessary VISTA NF-16D safety trips during calibration and/or validation. (R1)**[3]

## Handling Qualities Evaluation Tasks:

Phase 1, 2, and 3 handling qualities evaluations were performed. Descriptions of each phase are given below:

1. Phase 1: The evaluation pilot performed nonspecified gentle maneuvers, typically emphasizing control in the pitch axis, to get a feel for how the aircraft would handle during phases 2 and 3.

2. Phase 2: The evaluation pilot performed high bandwidth HQDT[4] using HUD tracking task No. 1. The evaluation pilot tracked the target while the safety pilot controlled the throttle to maintain 300 ±10 KCAS. After completion of the task, the pilot commented on aircraft handling qualities and assigned a PIO tendency rating (PIOR) using the scale in Appendix B (Figure B2). Due to the nature of HQDT, Cooper-Harper handling qualities ratings were not assigned for this phase of testing.

3. Phase 3: The evaluation pilot tracked the target displayed during HUD tracking task No. 2 using operationally realistic techniques. The evaluation pilot tracked the target while the safety pilot controlled the throttle to maintain 300 ±10 KCAS. After completion of the task, the evaluation pilot assigned a Cooper-Harper handling qualities rating using the following criteria:

    a. Desired: Remained inside the 20-milliradian diameter circle 50 percent of the time.

    b. Adequate: Remained inside the 40-milliradian diameter circle 50 percent of the time.

Figure 5 contains a description of the 20- and 40-milliradian diameter circles as displayed in the HUD. The pilot also evaluated PIO tendencies by assigning a PIOR using the scale in Appendix B (Figure B2).

## Recorded Parameters:

Numerous digital and analog parameters were recorded in flight. In addition to those parameters, HUD video and the safety pilot multifunctional display (MFD) were recorded for each test point. Cockpit audio was also recorded on the HUD tape. Pilot ratings and comments were documented immediately following each flight in conjunction with the videotape review.

# TEST RESULTS

All test objectives were met. The PIO and/or departure susceptibility was determined for both the HAFA 1 and HAFA 2 baseline aircraft and with various software rate limits with and without the RLPF. The PIO tendency and CHRs and pilot comments were collected at each test point.

In some cases, test points were reflown due to nuisance safety trips or inconclusive PIO and/or departure data. Appendix B contains PIO tendency and CHRs with their respective pilot comments for each test point.

The available and actual test matrices for this project are given in Table 3. Actual test points are indicated by the white boxes. Gray boxes indicate test points that were available to fly but were eliminated based on data obtained during calibration flights. Seventeen test points were completed for both the HAFA 1 and HAFA 2 aircraft (34 total test points).

## HAFA 1 and HAFA 2 Aircraft Validation:

The HAFA 1 and HAFA 2 baseline aircraft were validated using flight test data obtained during calibration and/or validation flights. The short period natural frequency and damping ratio, CAP, and $T_{\theta 2}$ (transfer function numerator zero determinant) based on a lower order equivalent system (LOES) time domain match of VISTA flight test step responses and frequency sweeps are shown in Table 4. Transfer functions, CAP calculations, and flight test step and frequency responses are given in Appendix A.

[3] Numerals preceded by an R within parenthesis at the end of a paragraph correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.
[4] The HQDT piloting technique is defined by the USAF TPS as: "Track a precision aim point as aggressively and assiduously as possible, always striving to correct even the smallest of tracking errors." (Reference 6)

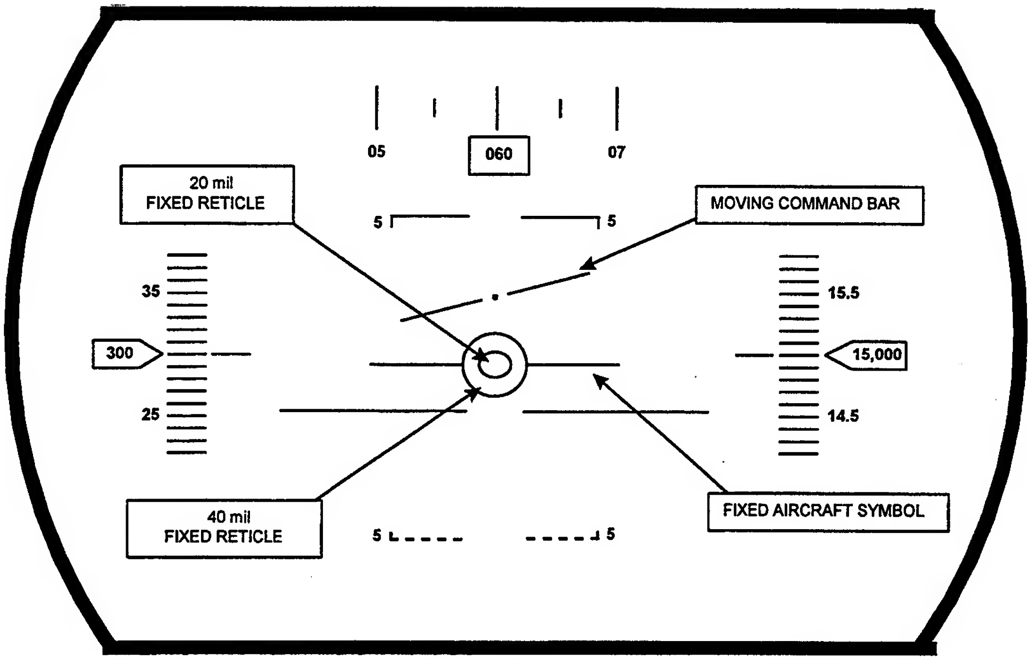


Figure 5 Flight Test Head-Up Display Setup

Table 3
AVAILABLE AND ACTUAL TEST MATRICES

| Configuration | SWRL (deg/s) | RLPF Thresholds (deg/s$^2$) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | None | 100 | 250 | 500 | 750 | 1,000 | 1,250 |
| HAFA 1 | None | 100 | NA | NA | NA | NA | NA | NA |
| | 55 | 110 | 111 | 112 | 113 | 114 | 115 | 116 |
| | 50 | 120 | 121 | 122 | 123 | 124 | 125 | 126 |
| | 45 | 130 | 131 | 132 | 133 | 134 | 135 | 136 |
| | 40 | 140 | 141 | 142 | 143 | 144 | 145 | 146 |
| | 35 | 150 | 151 | 152 | 153 | 154 | 155 | 156 |
| | 30 | 160 | 161 | 162 | 163 | 164 | 165 | 166 |
| | 25 | 170 | 171 | 172 | 173 | 174 | 175 | 176 |
| | 20 | 180 | 181 | 182 | 183 | 184 | 185 | 186 |
| HAFA 2 | None | 200 | NA | NA | NA | NA | NA | NA |
| | 55 | 210 | 211 | 212 | 213 | 214 | 215 | 216 |
| | 50 | 220 | 221 | 222 | 223 | 224 | 225 | 226 |
| | 45 | 230 | 231 | 232 | 233 | 234 | 235 | 236 |
| | 40 | 240 | 241 | 242 | 243 | 244 | 245 | 246 |
| | 35 | 250 | 251 | 252 | 253 | 254 | 255 | 256 |
| | 30 | 260 | 261 | 262 | 263 | 264 | 265 | 266 |
| | 25 | 270 | 271 | 272 | 273 | 274 | 275 | 276 |
| | 20 | 280 | 281 | 282 | 283 | 284 | 285 | 286 |

Notes: 1. SWRL - software rate limit
2. RLPF - nonlinear rate limiter pre-filter
3. NA - not applicable
4. Gray boxes indicate available test points not flown.

Table 4
HAFA 1 AND HAFA 2 LOWER ORDER EQUIVALENT SYSTEM MATCHES

| Aircraft | $\omega_{sp}$ (rad/sec) | $\zeta_{sp}$ | CAP (1/g/sec$^2$) | $T_{\theta 2}$ (sec) |
|---|---|---|---|---|
| HAFA 1 | 4.64 | 0.700 | 0.718 - level 1 | 0.65 |
| HAFA 2 | 1.80 | 0.654 | 0.108 - level 3 | 0.65 |

Notes: 1. $\omega_{sp}$ - short period natural frequency
2. $\zeta_{sp}$ - short period damping ratio
3. CAP - Control Anticipation Parameter
4. $T_{\theta 2}$ - transfer function numerator zero determinant

## Baseline Aircraft Response:

The purpose in characterizing the baseline aircraft response was to form a basis from which comparisons with SWRL and RLPF plus SWRL configurations could be made. Characterizations of the HAFA 1 and HAFA 2 baseline aircraft are given below.

## Baseline Aircraft Departure/Pilot-Induced Oscillation Susceptibility.

Departure and/or PIO susceptibility was determined for both the HAFA 1 and HAFA 2 baseline aircraft.

Table 5 identifies departure tendencies for these aircraft during both the HQDT and operational tracking tasks. Similar tables are presented in later sections for comparison between the baseline aircraft and those configurations containing a software rate limit and the nonlinear rate limiter pre-filter algorithm. For each departure and/or PIO susceptibility table, those configurations that did not depart are designated with an "N." Configurations that clearly departed, causing a VISTA safety trip (typically, the *pitch_monitor* safety trip), are labeled with a "D." Configurations where flight test data and pilot observations were inconclusive in determining whether a safety trip represented a departure or merely a nuisance safety trip are represented by an "I." The PIO tendency and CHRs were not assigned for "I" configurations.

Handling qualities during tracking (HQDT) helped to identify potential departure and PIO problems that were not observed during phase 3 operational tracking. Departure was observed more often during HQDT than operational tracking for all HAFA 1 configurations tested. As shown above, the HAFA 1 aircraft departed nearly every time during HQDT and for two of the three test pilots during the operational tracking task. Pilot C was the only pilot who did not observe a departure during the operational tracking task.

The HAFA 2 aircraft was not as susceptible to departure as the HAFA 1 aircraft. No departures were observed during operational tracking. One HQDT run produced inconclusive departure data.

Typical flight test data for the HAFA 1 aircraft during operational tracking are shown in Figure 6. Figure 6 shows the aircraft body axis pitch angle following the tracking task profile. The HAFA 1 baseline aircraft departed controlled flight approximately 47 seconds into the tracking task. Departure occurred as a result of a large pull as the pilot attempted to capture the task. The pilot was unable to stop the commanded pitch rate leading to departure. This type of departure was observed during simulations in Large Amplitude Multimode Aerospace Simulator (Reference 1).

## Baseline Aircraft Handling Qualities.

Handling qualities were assessed during phase 2 HQDT and phase 3 operational tracking tasks. The PIO and CHRs for the HAFA 1 aircraft are graphically displayed in Figures 7 and 8. Likewise, ratings for the HAFA 2 aircraft are given in Figures 9 and 10.

## HAFA 1 Aircraft

The HAFA 1 aircraft exhibited PIO tendencies during the HQDT task. Initial pitch response was very twitchy resulting in pitch bobbles during pitch captures. Oscillations quickly grew leading to departures in many instances.

During phase 3 operational tracking, the aircraft departed for two pilots. A crisp initial pitch response made gross acquisition captures difficult during operational tracking. Pitch bobbles during fine tracking resulted in pilots achieving only adequate performance in many cases. Pilot C, who did not depart, thought this configuration was "on a tight rope, could depart at any time." Medium to high pilot compensation was required for all tracking tasks.

Table 5
BASELINE AIRCRAFT DEPARTURE AND/OR PILOT-INDUCED OSCILLATION SUSCEPTIBILITY

**HAFA 1 Phase 2**
**Handling Qualities During Tracking (HQDT)**

| Pilot A | | Pilot B | | Pilot C | |
|---|---|---|---|---|---|
| D | D* | D | N | D | D |

*Large amplitude HQDT task

**HAFA 2 Phase 2**
**Handling Qualities During Tracking**

| Pilot A | | Pilot B | | Pilot C | |
|---|---|---|---|---|---|
| I* | N | N | N | N | N |

*Large amplitude HQDT task

**HAFA 1 Phase 3**
**Operational Evaluation**

| Pilot A | | Pilot B | | Pilot C | |
|---|---|---|---|---|---|
| D | D | D | N | N | N |

**HAFA 2 Phase 3**
**Operational Evaluation**

| Pilot A | | Pilot B | | Pilot C | |
|---|---|---|---|---|---|
| N | N | N | N | N | N |

D = Departure
N = No Departure
I = Inconclusive Data

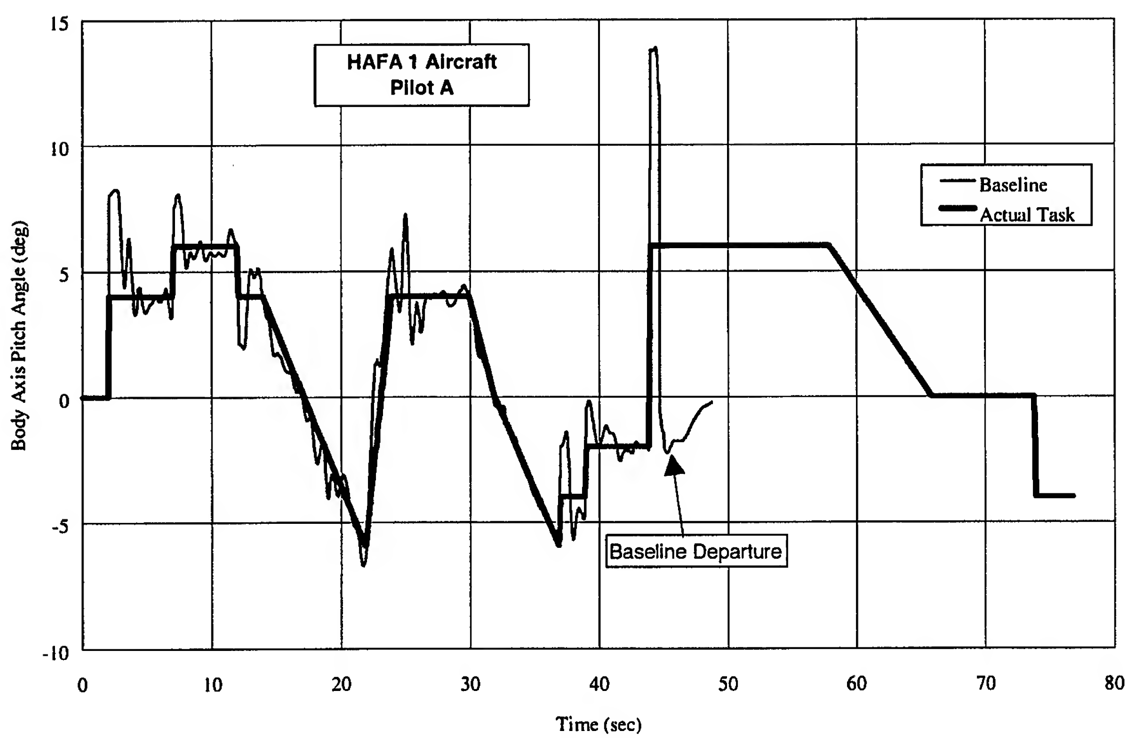


Figure 6 Baseline Tracking Task Response


Figure 7 HAFA 1 Baseline Handling Qualities During Tracking Pilot-Induced Oscillation Tendency Ratings

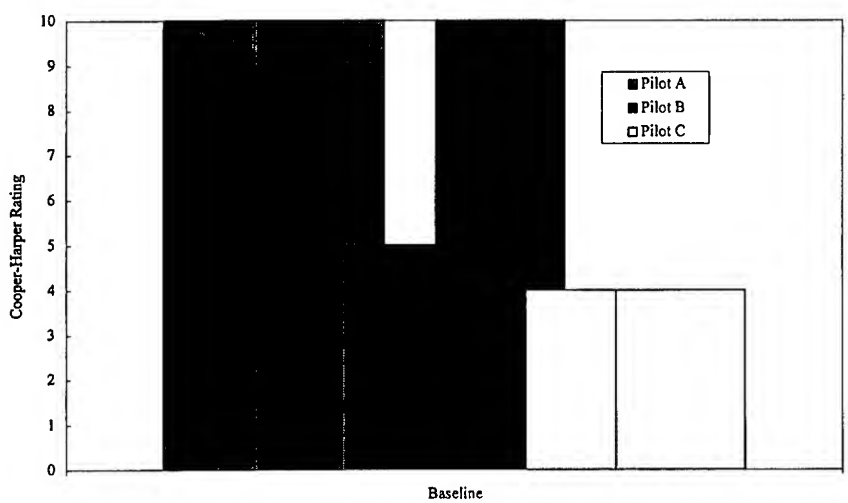


Figure 8 HAFA 1 Baseline Operational Evaluation Cooper-Harper Ratings

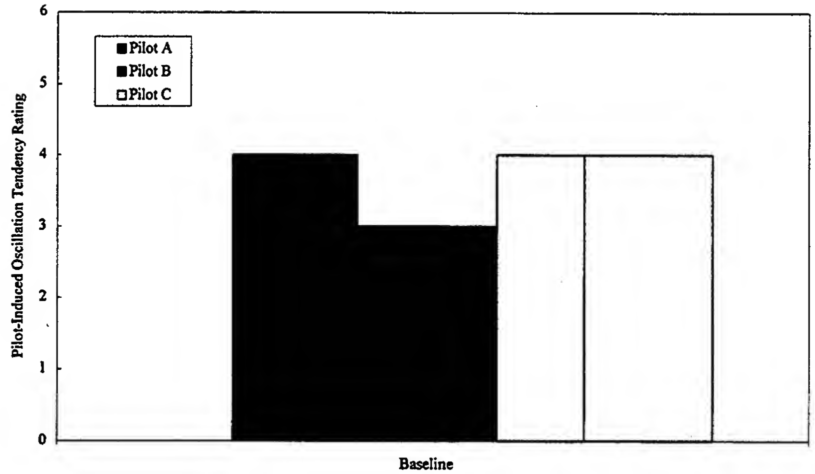


Figure 9 HAFA 2 Baseline Handling Qualities During Tracking Pilot-Induced Oscillation Tendency Ratings

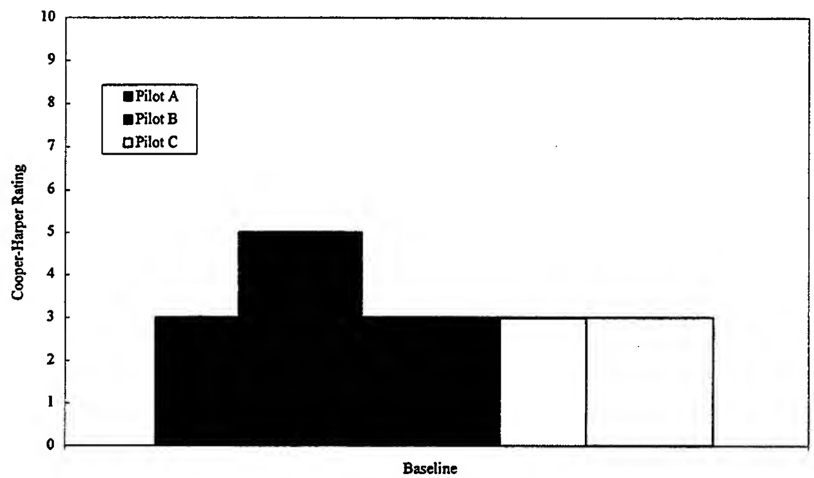


Figure 10 HAFA 2 Baseline Operational Evaluation Cooper-Harper Ratings

## HAFA 2 Aircraft

The HAFA 2 aircraft received slightly better PIO ratings than the HAFA 1 aircraft during HQDT. Pilots generally observed a small delay in pitch response followed by a steady ramp up in pitch rate. Stop-to-stop control inputs did not cause divergent oscillations, but caused nuisance safety trips on many occasions.

During phase 3 operational tracking, the aircraft did not depart and received significantly better CHRs than for the HAFA 1 aircraft. The CHR for this aircraft classified it as level 1 despite MIL-STD 1797A (Reference 3) CAP predictions. Hence, CAP alone did not adequately predict aircraft handling qualities. Pilots observed an initial sluggishness and large overshoots during gross acquisition. Fine tracking was much easier than for the HAFA 1 aircraft as the aircraft was well behaved and predictable. One pilot surmised a larger pitch task might degrade performance because the large overshoots were difficult to arrest.

## Software Rate Limiter Effects:

A software rate limiter (SWRL) was added to the pilot command of the baseline aircraft. Software rate limits of 50, 40, 35, 30, and 20 degrees per second were tested (see Table 3). A typical aircraft response with the SWRL set at 20 degrees per second is shown in Figure 11. Plotted in Figure 11 are the pilot command and the output of the SWRL (command to the outer feedback loop of the flight control system). The sawtooth pattern indicates that the pilot is commanding a higher rate of deflection of the horizontal stabilator than the SWRL setting allows. Notice that reversals do not occur in phase with the pilot command. In addition, the slope of the SWRL Output line is 20 degrees per second, corresponding to the set SWRL for this particular configuration.

### Departure and/or Pilot-Induced Oscillation Susceptibility with Software Rate Limiter.

Departure and/or PIO susceptibility was determined for both the HAFA 1 and HAFA 2 baseline aircraft with the addition of a SWRL on the pilot command. Table 6 identifies departure tendencies for these configurations during both the HQDT and operational tracking (HUD tracking task No. 2) tasks.

Table 6 shows that as the SWRL was decreased to 30 degrees per second during HQDT, departure was prevented for even the most aggressive pilot (Pilot A) on the HAFA 1 aircraft. Again, more departures were observed for the HAFA 1 aircraft during HQDT than during operational tracking, highlighting potential problems. Data from several test points were not sufficient to determine whether the aircraft departed or the test aircraft experienced a nuisance safety trip. Those points are identified by an "I."

Minimal software rate limiting prevented departure on the HAFA 1 aircraft during phase 3 operational tracking for all pilots except Pilot A. The aircraft departed for Pilot A with SWRL set as low as 35 degrees per second. Lower SWRL settings prevented departure for this pilot. While Pilot B did not observe departure at higher SWRL settings, the aircraft curiously departed twice with the SWRL set to 30 degrees per second. Pilot C did not observe any departures during this task.

Tracking task response for the HAFA 1 baseline aircraft is compared to the response observed for an aircraft with a software rate limit of 40 degrees per second in Figure 12. The baseline trace is the same data displayed in Figure 6. Response throughout the early portion of the task is similar. The only noticeable difference occurred at the 25-second point where the rate limited configuration did a slightly better job in minimizing overshoots. Eventually, both aircraft departed at nearly the same point in the task, however, the rate-limited configuration lasted a couple additional stick cycles before safety trips were exceeded.

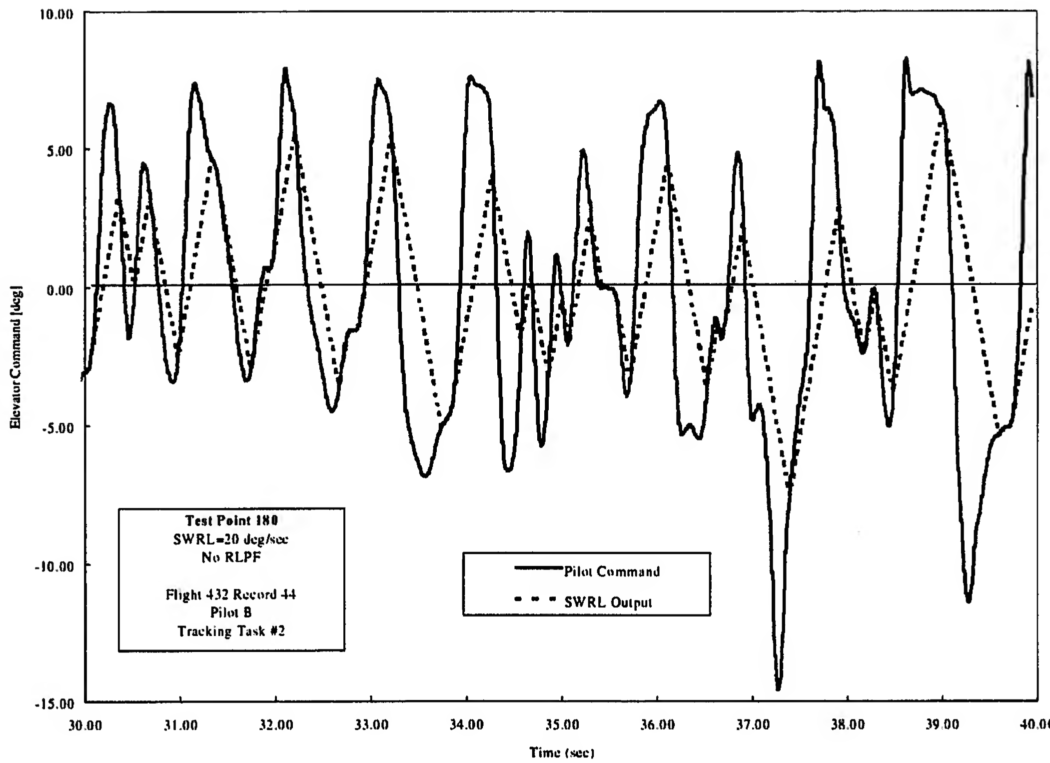


Figure 11 Software Rate Limiter Example

Table 6
SOFTWARE RATE LIMITER (SWRL) EFFECTS ON DEPARTURE/PILOT-INDUCED OSCILLATION SUSCEPTIBILITY

**HAFA 1 Phase 2**
**Handling Qualities During Tracking (HQDT)**

| SWRL deg/s | Pilot A | | Pilot B | | Pilot C | |
|---|---|---|---|---|---|---|
| Baseline | D | D* | D | N | D | D |
| 50 | D | | D | | D | |
| 40 | D | | D | | D | |
| 35 | D | | D | | I | |
| 30 | N | N | I | I | I | N |
| 20 | I* | | N | N | N | I |

*Large amplitude HQDT task

**HAFA 2 Phase 2**
**Handling Qualities During Tracking**

| SWRL deg/s | Pilot A | | Pilot B | | Pilot C | |
|---|---|---|---|---|---|---|
| Baseline | I* | N | N | N | N | N |
| 50 | I* | | N | | N | |
| 40 | N | I | I | I | N | I |
| 35 | I* | | N | | I | |
| 30 | N | | N | | N | |
| 20 | N* | | N | | I | |

*Large amplitude HQDT task

**HAFA 1 Phase 3**
**Operational Evaluation**

| SWRL deg/s | Pilot A | | Pilot B | | Pilot C | |
|---|---|---|---|---|---|---|
| Baseline | D | D | D | N | N | N |
| 50 | D | | N | | N | |
| 40 | D | | N | | N | |
| 35 | D | | N | | N | |
| 30 | I | N | D | D | N | N |
| 20 | N | | N | N | N | N |

**HAFA 2 Phase 3**
**Operational Evaluation**

| SWRL deg/s | Pilot A | | Pilot B | | Pilot C | |
|---|---|---|---|---|---|---|
| Baseline | N | N | N | N | N | N |
| 50 | N | | N | | N | |
| 40 | I | N | N | N | N | N |
| 35 | N | | N | | N | |
| 30 | N | | N | | N | |
| 20 | N | | N | | N | |

Notes:
1. D - departure
2. N - no departure
3. I - inconclusive data
4. RLPF - nonlinear rate limiter pre-filter
5. SWRL - software rate limit
6. Shaded boxes indicate test points that were not flown.

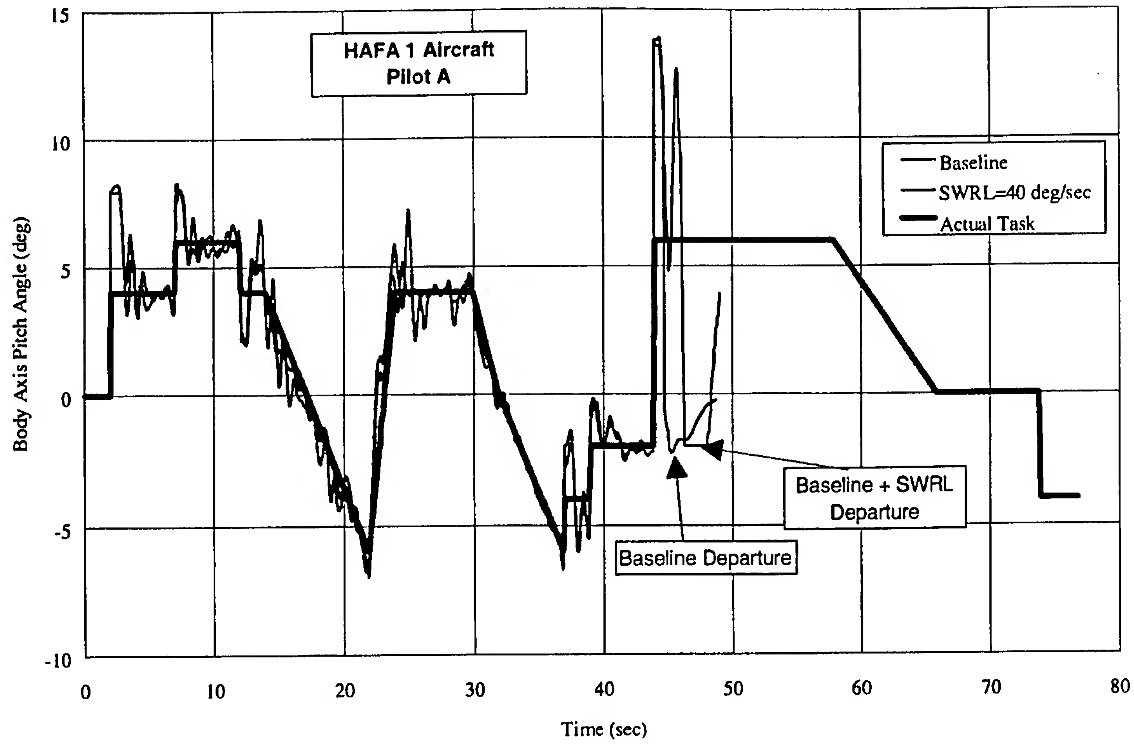


Figure 12 Software Rate Limit Tracking Task Response

## Handling Qualities with Software Rate Limiter:

Handling qualities were assessed during phase 2 HQDT and phase 3 operational tracking tasks. The PIO and CHRs for the HAFA 1 aircraft are graphically displayed in Figures 13 and 14. Likewise, ratings for the HAFA 2 aircraft are given in Figures 15 and 16.

### HAFA 1 Aircraft

Software rate limiting the pilot command did not have an appreciable effect on PIO ratings during HQDT for the HAFA 1 aircraft through approximately 35 degrees per second. Initial pitch response was good at all SWRL settings. The aircraft felt in phase at higher SWRL settings, i.e., 50 degrees per second, and progressed to feeling out-of-phase at very low SWRL settings, i.e., 20 degrees per second.

In general, for the phase 3 task, decreasing software rate limit settings resulted in higher CHRs. Even though PIO ratings improved slightly below 30 degrees per second during HQDT, pilot comments indicated just the opposite during operational tracking. As the SWRL was decreased, gross acquisition became increasingly difficult as the pilots attempted to arrest fairly large overshoots. Pilots had to back out of the loop to prevent PIO with the SWRL set to 35 degrees per second or below. While fine tracking workload remained relatively constant throughout the range of SWRL settings tested, gross acquisition workload increased. Many pilots noted that a pitch rate buildup following a nice initial pitch response was unpredictable resulting in multiple, large overshoots. This behavior correlates with the tracking performance shown in Figure 12. At the point of departure, the pilot experienced multiple, large overshoots before the test aircraft safety trips were exceeded.

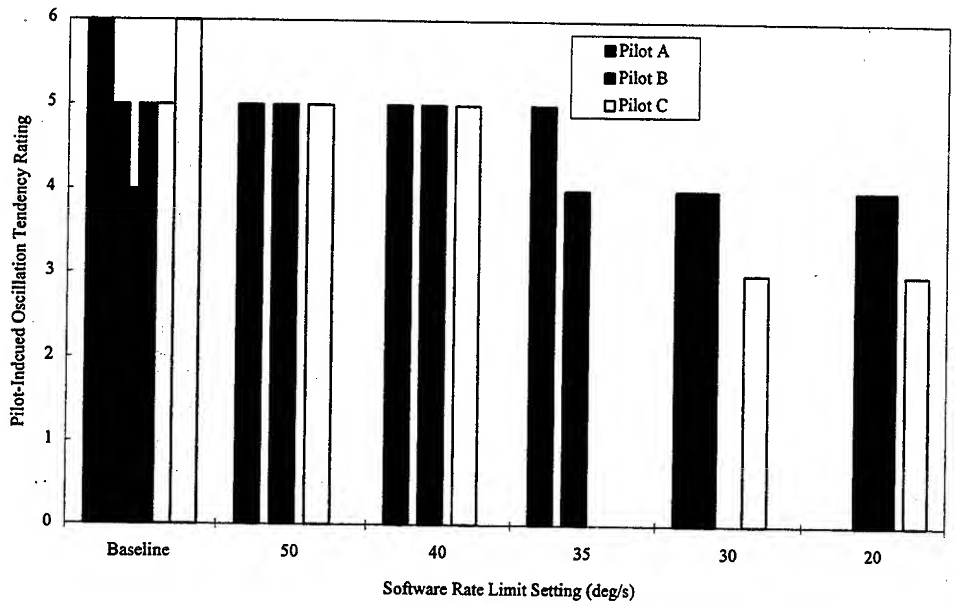


Figure 13 HAFA 1 Software Rate Limiter Effects on Handling Qualities During Tracking Pilot-Induced Oscillation Tendency Ratings

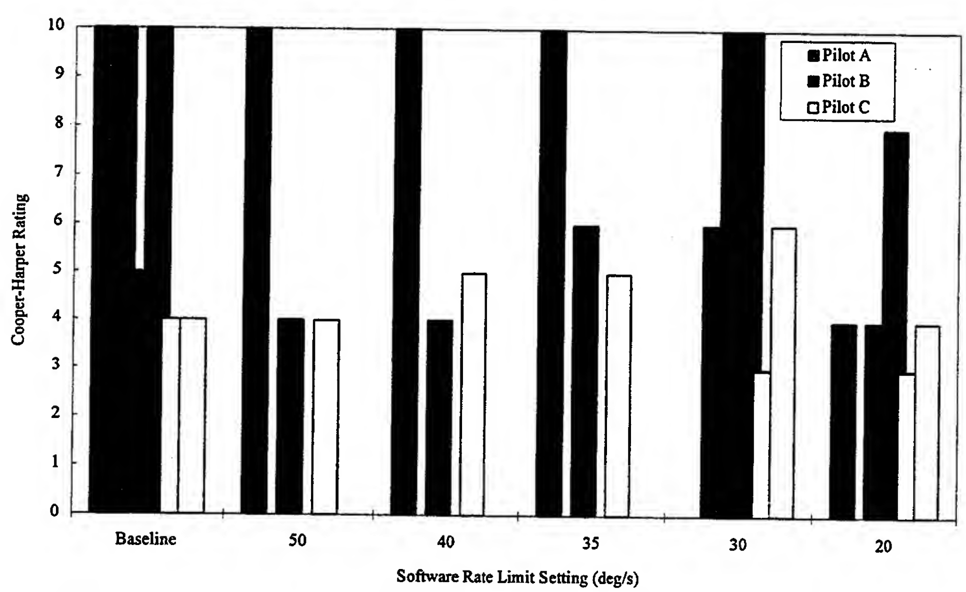


Figure 14 HAFA 1 Software Rate Limiter Effects on Phase 3 Cooper-Harper Ratings

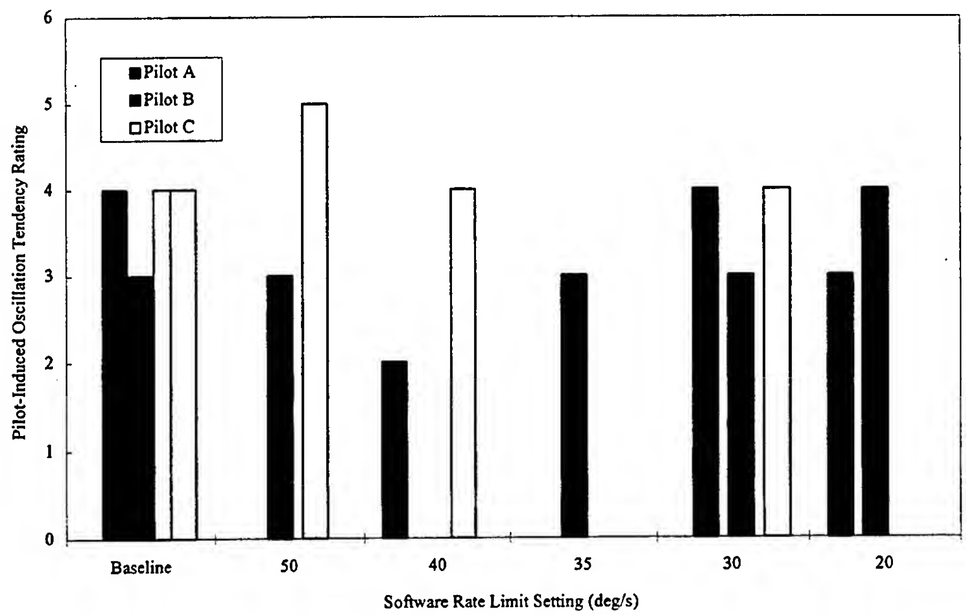


Figure 15 HAFA 2 Software Rate Limiter Effects on Handling Qualities During Tracking Pilot-Induced Oscillation Tendency Ratings

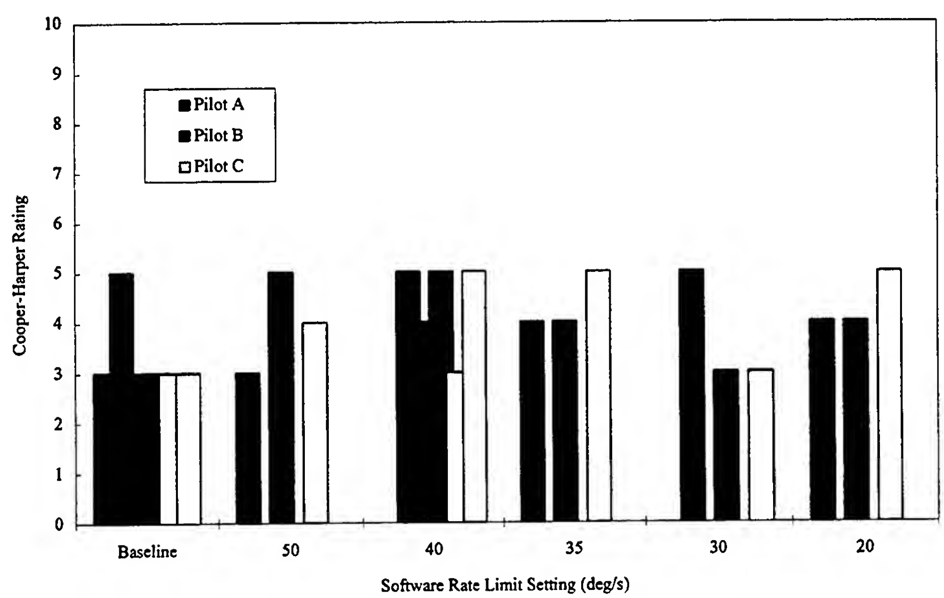


Figure 16 HAFA 2 Software Rate Limiter Effects on Phase 3 Cooper-Harper Ratings

## HAFA 2 Aircraft

The PIO ratings for the HAFA 2 aircraft were scattered across the range of SWRL settings tested. For HQDT, the pilots agreed the aircraft was generally slow to respond, making it hard to reverse flight path. Numerous nuisance safety trips occurred during stop-to-stop HQDT.

Software rate limiting had a negligible effect on CHR for the HAFA 2 aircraft during the operational tracking task. Task performance was usually adequate with more frequent desired ratings at higher SWRL settings. As mentioned previously for the baseline configuration, CHRs for the HAFA 2 aircraft were significantly better than those assigned to the HAFA 1 aircraft with the same SWRL settings. The aircraft was increasingly sluggish in initial pitch response as the SWRL was decreased. This sluggishness resulted in increasing unpredictability and made gross acquisition quite difficult. Fine tracking, however, was generally enhanced by the sluggishness.

## Nonlinear Rate Limiter Pre-Filter Effects:

The RLPF algorithm was added to the pilot command before the SWRL (Figure A7). With the SWRL only (configuration B), the SWRL output was biased off command during rate limiting (Figure 11) and did not stay in phase with the input. Once rate limited inputs ceased, the bias disappeared as the output caught up to the command.

The RLPF, however, was designed to operate in conjunction with the SWRL and allow nearly in-phase reversing with the pilot command. With the RLPF plus SWRL, bias did not automatically catch up but was removed by the RLPF logic when neither the SWRL nor the stick acceleration threshold was exceeded (Figure A8). For this test, the acceleration threshold for bias removal was set to 100 degrees per second squared (degrees per second$^2$). Initially, other threshold settings were expected to be tested (see Table 3). Previous simulations using a centerstick in LAMARS showed stick accelerations above 1,000 degrees per second$^2$ (Reference 1). However, calibration flights indicated the pilot was not commanding stick accelerations above 250 degrees per second$^2$. Figure 17 shows actual commanded stick accelerations typically observed for both the HAFA 1 and HAFA 2 baseline aircraft.

With the acceleration threshold set above the maximum commanded acceleration value, the filter would function similarly to the software rate limit, i.e., somewhat (but not as much) out-of-phase reversals. However, the algorithm would still command trim bias removal when the software rate limit was not exceeded. Configurations such as these, where the acceleration threshold was set too high, were not evaluated based on poor simulation results.

For both the HAFA 1 and HAFA 2 aircraft, the RLPF functioned as designed. A typical response is shown in Figure 18 for a portion of the phase 3 HUD tracking task. The data showed that the algorithm commanded in-phase reversals and trim bias removal as designed.

## Departure and/or Pilot-Induced Oscillation Susceptibility with Nonlinear Rate Limiter Pre-Filter plus Software Rate Limit.

Departure and/or PIO susceptibility was determined for both the HAFA 1 and HAFA 2 baseline plus SWRL combination with the addition of the nonlinear RLPF algorithm before the SWRL. Table 7 identifies departure tendencies for these configurations during both the HQDT and operational tracking (HUD tracking task No. 2) tasks.

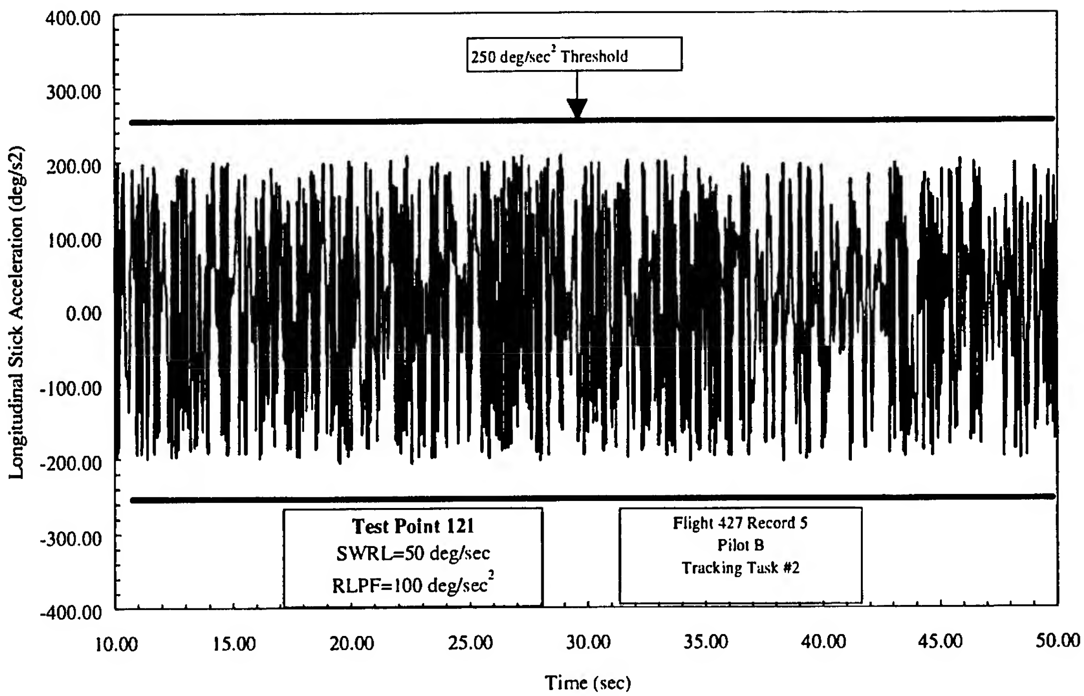


Figure 17 Pilot Commanded Stick Accelerations

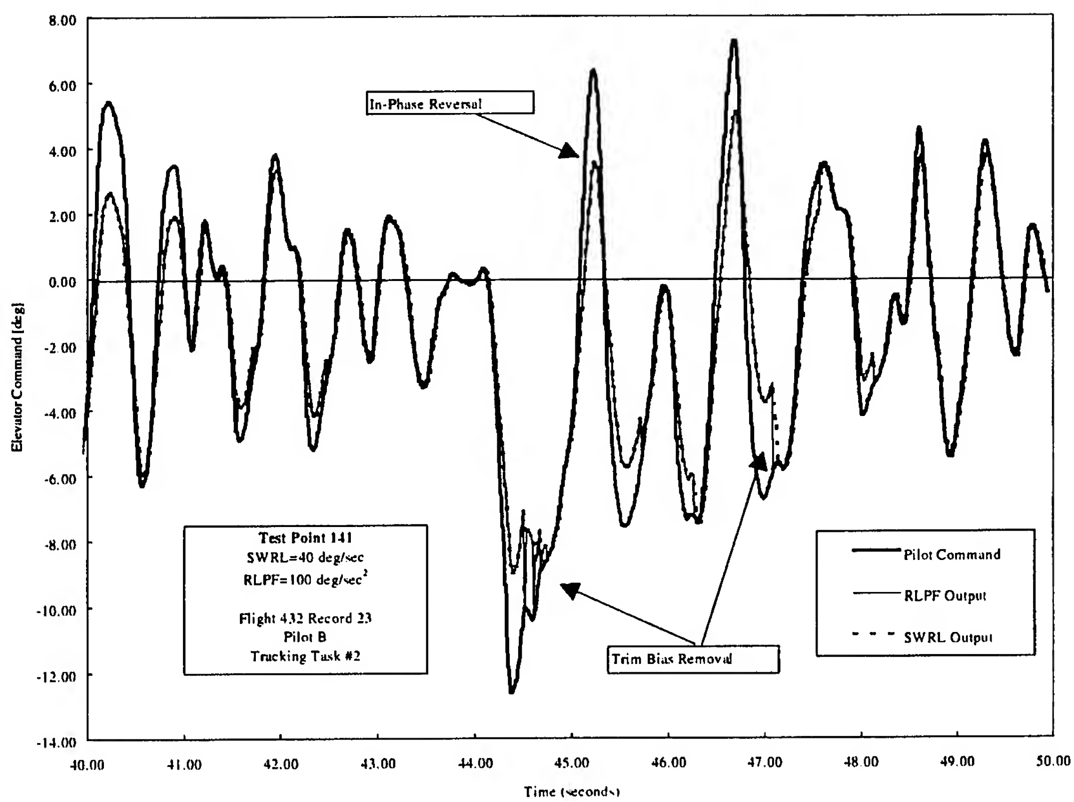


Figure 18 Nonlinear Rate Limiter Pre-Filter Operation

Table 7
NONLINEAR RATE LIMITER PRE-FILTER EFFECTS ON DEPARTURE
AND/OR PILOT-INDUCED OSCILLATION SUSCEPTIBILITY

**HAFA 1 Handling Qualities During Tracking (HQDT)**

| **SWRL** | **RLPF=None** | | | | | | **RLPF=100 deg/s$^2$** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| deg/s | Pilot A | | Pilot B | | Pilot C | | Pilot A | | Pilot B | | Pilot C | |
| Baseline | D | D* | D | N | D | D | | | | | | |
| 50 | D | | D | | D | | D* | | N | | N | |
| 40 | D | | D | | D | | N | D | N | D | D | N |
| 35 | D | | D | | I | | N | N | N | I | D | N |
| 30 | N | N | I | I | I | N | N | I | N | I | N | I |
| 20 | I* | | N | N | N | I | N | I* | N | I | N | I |

*Large amplitude HQDT task

**HAFA 1 Operational Evaluation**

| **SWRL** | **RLPF=None** | | | | | | **RLPF=100 deg/s$^2$** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| deg/s | Pilot A | | Pilot B | | Pilot C | | Pilot A | | Pilot B | | Pilot C | |
| Baseline | D | D | D | N | N | N | | | | | | |
| 50 | D | | N | | N | | D | | N | | I | |
| 40 | D | | N | | N | | N | N | N | N | N | N |
| 35 | D | | N | | N | | N | I | N | N | N | N |
| 30 | I | N | D | D | N | N | N | N | N | N | N | N |
| 20 | N | | N | N | N | N | N | I | N | N | N | N |

**HAFA 2 Handling Qualities During Tracking**

| **SWRL** | **RLPF=None** | | | | | | **RLPF=100 deg/s$^2$** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| deg/s | Pilot A | | Pilot B | | Pilot C | | Pilot A | | Pilot B | | Pilot C | |
| Baseline | I* | N | N | N | N | N | | | | | | |
| 50 | I* | | N | | N | | N* | | I | | N | |
| 40 | N | I | I | I | N | I | N | I | I | N | I | I |
| 35 | I* | | N | | I | | N | N | I | N | I | N |
| 30 | N | | N | | N | | I | N | I | N | N | N |
| 20 | N* | | N | | I | | I* | N | N | N | I | I |

*Large amplitude HQDT task

**HAFA 2 Operational Evaluation**

| **SWRL** | **RLPF=None** | | | | | | **RLPF=100 deg/s$^2$** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| deg/s | Pilot A | | Pilot B | | Pilot C | | Pilot A | | Pilot B | | Pilot C | |
| Baseline | N | N | N | N | N | N | | | | | | |
| 50 | N | | N | | N | | N | | N | | N | |
| 40 | I | N | N | N | N | N | N | N | N | N | I | N |
| 35 | N | | N | | N | | I | I | N | N | N | N |
| 30 | N | | N | | N | | I | N | N | N | N | N |
| 20 | N | | N | | N | | I | N | N | N | N | N |

Notes:
1. D - departure
2. N - no departure
3. I - inconclusive data
4. RLPF - nonlinear rate limiter pre-filter
5. SWRL - software rate limiter
6. Shaded boxes indicate test points that were not flown.

The addition of the RLPF algorithm reduced departure susceptibility for a given SWRL setting on the HAFA 1 aircraft for both phase 2 and 3 tasks. Following the progression of configurations from the baseline through the addition of a software rate limit of 40 degrees per second to the addition of the RLPF with the 35 degrees per second SWRL, one could see the difference in departure susceptibility. Where the baseline and SWRL configurations departed, the RLPF plus SWRL almost always prevented departure. Since the baseline HAFA 2 aircraft was not prone to departure, changes in departure susceptibility were not evident.

A sample tracking task response is shown in Figure 19. The red trace is the baseline aircraft response shown in Figure 6. The blue trace is the SWRL configuration shown in Figure 12. The green trace is the RLPF plus SWRL configuration with a SWRL setting equal to that for the blue trace. As shown, the RLPF plus SWRL configuration completes the tracking task whereas the baseline and SWRL only configurations depart controlled flight around 45 seconds into the task.

## **Handling Qualities with Rate Limiter Pre-Filter plus Software Rate Limiter.**

Handling qualities were assessed during phase 2 HQDT and phase 3 operational tracking tasks. One reason for poor pilot comments and ratings for RLPF plus low SWRL settings was a large bias buildup following aggressive maneuvering that resulted in a positive command (input) but negative output or vice versa. A large bias buildup example from an operational tracking task is shown in Figure 20. The PIO and CHRs for the HAFA 1 aircraft are graphically displayed in Figures 21 and 22. Likewise, ratings for the HAFA 2 aircraft are given in Figures 23 and 24.

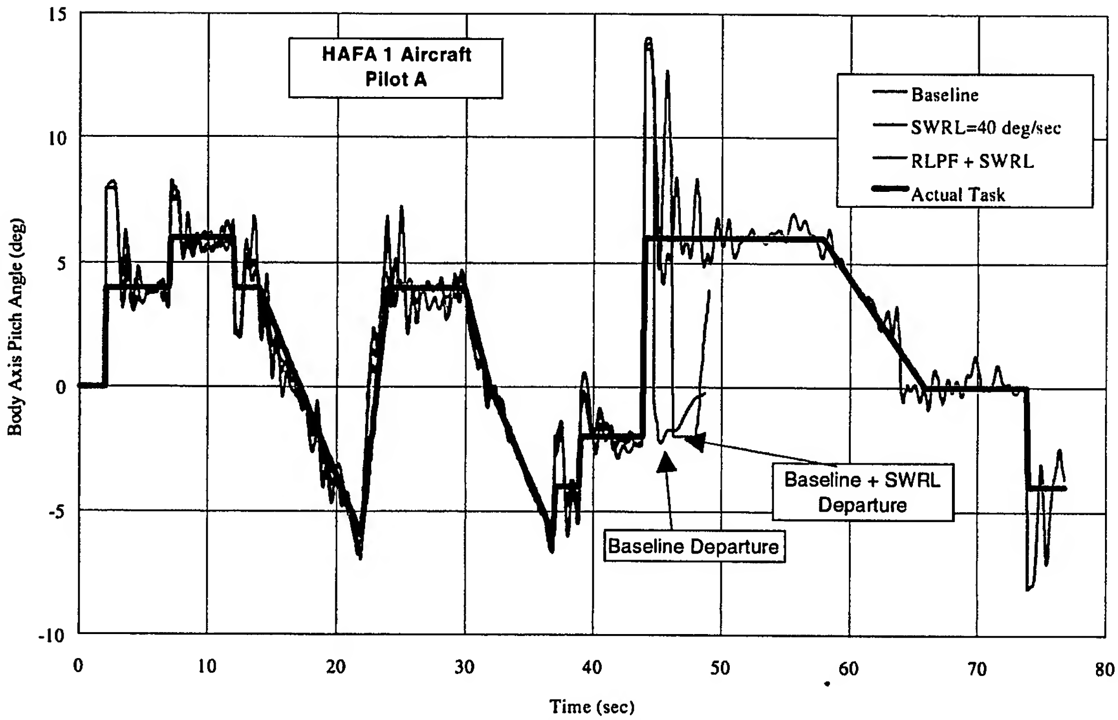


Figure 19 Operational Tracking Task Response Comparison

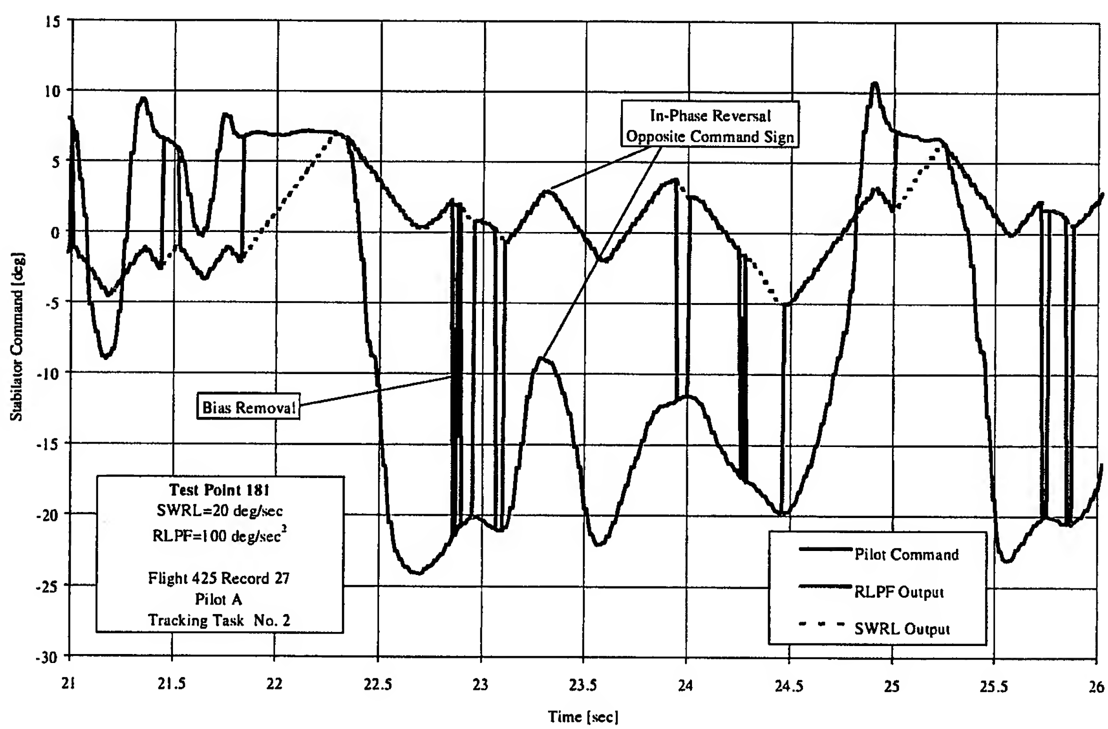


Figure 20 Nonlinear Rate Limiter Pre-filter (RLPF) Plus Low Software Rate Limiter (SWRL) Response

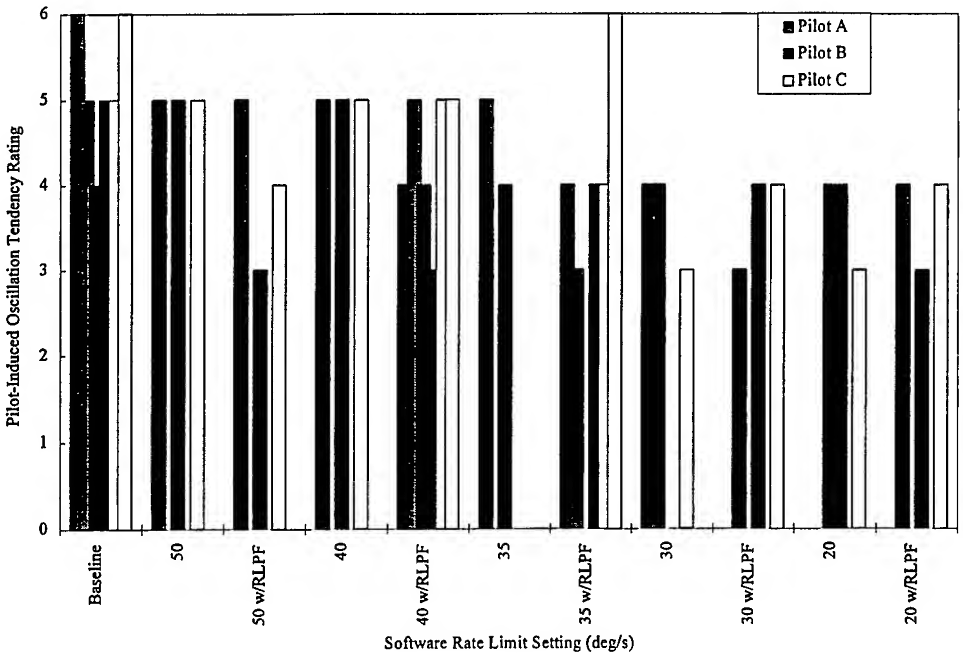


Figure 21 HAFA 1 Nonlinear Rate Limiter Pre-filter (RLPF) Effects on Handling Qualities During Tracking Pilot-Induced Oscillation Tendency Ratings (RLPF = 100 degrees per second$^2$)

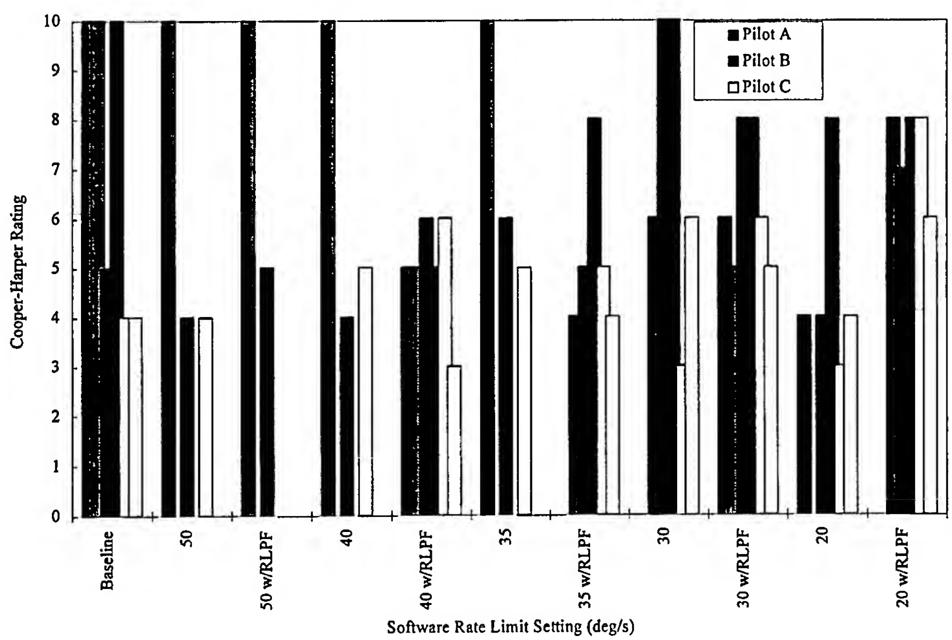


Figure 22 HAFA 1 Nonlinear Rate Limiter Pre-filter (RLPF) Effects on Phase 3 Cooper-Harper Ratings (RLPF = 100 degrees per second$^2$)

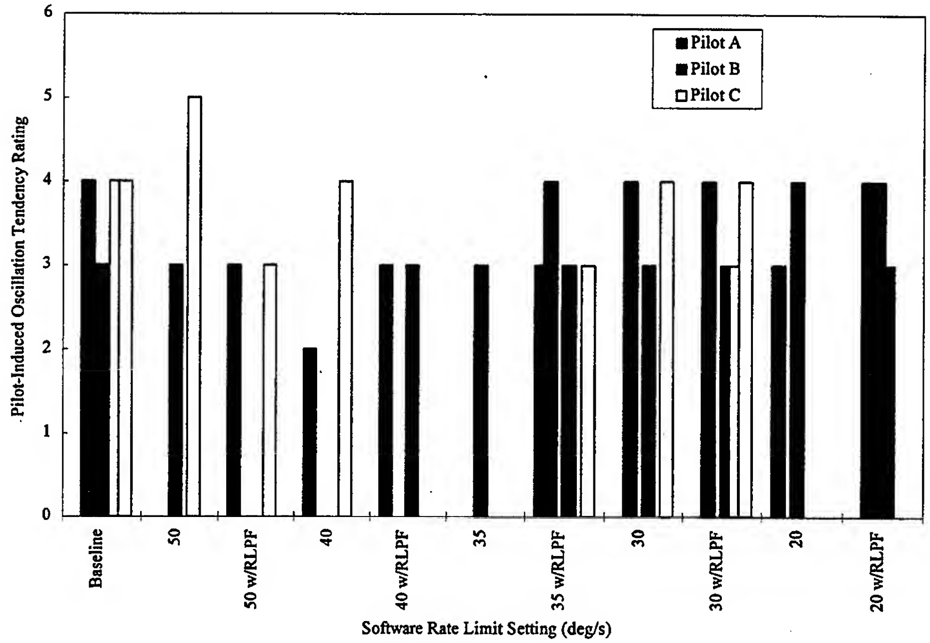


Figure 23 HAFA 2 Nonlinear Rate Limiter Pre-filter (RLPF) Effects on Handling Qualities During Tracking Pilot-Induced Oscillation Tendency Ratings (RLPF = 100 degrees per second$^2$)

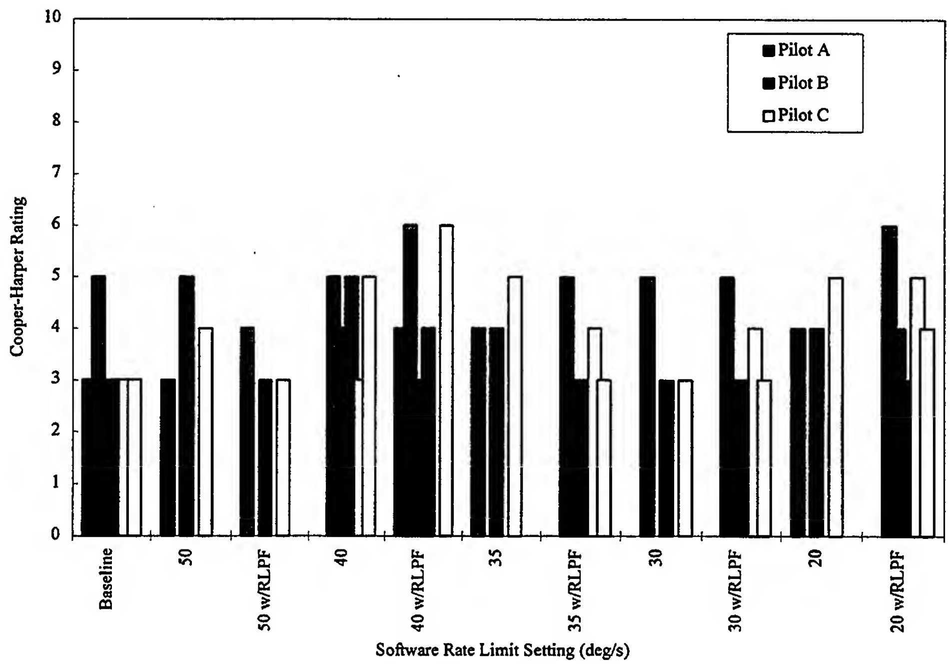


Figure 24 HAFA 2 Nonlinear Rate Limiter Pre-filter (RLPF) Effects on Phase 3 Cooper-Harper Ratings (RLPF = 100 degrees per second$^2$)

## HAFA 1 Aircraft

The addition of the RLPF on the pilot command during HQDT resulted in better PIO ratings (in-phase reversal) except at low SWRL settings. With a low SWRL setting, the response in both HQDT and operational tracking seemed uncommanded at times.

For phase 3 operational tracking, the addition of the RLPF to the SWRL increasingly degraded handling qualities as SWRL settings were lowered. Gross acquisition was sometimes crisper (in-phase reversal plus bias removal), but pitch bobbles hampered fine tracking. For RLPF plus low SWRL setting configurations, extreme pilot compensation was required and pilots observed that pitch rate appeared to be changing throughout the task. Poor handling qualities frequently prevented attainment of adequate criteria.

## HAFA 2 Aircraft

The addition of the RLPF did not change PIO ratings for the HAFA 2 aircraft during HQDT across the range of SWRL settings tested. Ratings also did not change appreciably from the baseline configuration. Pitch response was quite sluggish and unpredictable for low software rate limit configurations. Although the initial pitch response was sluggish, gross acquisition was not degraded significantly due to the deadbeat response once pilot input was removed. There was little tendency for PIO throughout.

During operational tracking, assigned CHRs for RLPF plus SWRL configurations were similar to those assigned to SWRL and baseline aircraft configurations. Pilot comments were similar to those recorded for SWRL only configurations. The aircraft was sluggish in pitch but very steady during fine tracking. There was no sense of changing flight control system gains or variable pitch rate response as was observed during the HAFA 1 evaluation. The pilots felt in command of the aircraft throughout the tracking task.

# CONCLUSIONS AND RECOMMENDATION

The software rate limiter (SWRL) placed on the pilot command path of the predicted level 1 highly-augmented fighter aircraft (HAFA 1) flight control system was successful at preventing departure and/or pilot-induced oscillation (PIO).

Low (less than 40 degrees per second) SWRL settings degraded handling qualities. The aircraft initial pitch response was sluggish during gross acquisition.

The nonlinear rate limiter pre-filter (RLPF) used in conjunction with the SWRL for the HAFA 1 configuration provided more departure and/or PIO protection than the SWRL alone.

The use of the RLPF at low SWRL settings (less than 40 degrees per second) sometimes displayed additional handling qualities deficiencies. Although bias removal was inherent in the RLPF algorithm, a large bias buildup during aggressive maneuvering sometimes led to apparent nonresponsive or opposite pitch commands.

The MIL-STD 1797A Control Anticipation Parameter (CAP) (Reference 3) was unreliable for predicting handling qualities ratings for this test. The predicted level 1 configuration (HAFA 1) was evaluated more like a level 2 aircraft and the predicted level 3 configuration (HAFA 2) was evaluated more like a level 1 aircraft.

The handling qualities during tracking (HQDT) technique was valuable at uncovering PIO and/or departure susceptibility.

Nuisance safety trips prevented useful data at many test points. After removing the appropriate safety trips, most nuisance safety trips disappeared.

***1. To save valuable flight test time and resources, remove unnecessary VISTA NF-16D safety trips during calibration and/or validation. (Page 7)***

This page intentionally left blank.

# REFERENCES


1. Chapa, Mike, Captain, USAF, *A Nonlinear Pre-Filter to Prevent Pilot-Induced Oscillations Due to Rate Limiting,* MS Thesis, AFIT/GAE/ENY/99M-0X. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB, Ohio, March 1999.

2. Ohmit, E.E. *NT-33 In-Flight Investigation into Flight Control System Rate Limiting*. Final Report No. 7738-24, Advanced Technology Center, Calspan Corporation, Buffalo, New York, February 1994.

3. Flying Qualities of Piloted Aircraft, MIL-STD 1797A.

4. Kish, Brian, Captain, USAF, *A Limited Flight Test Investigation of Pilot-Induced Oscillation Due to Elevator Rate Limiting (HAVE LIMITS)*, AFFTC-TR-97-12, USAF Test Pilot School, Air Force Flight Test Center, Edwards AFB, California, December 1997.

5. *NF-16D 86-0048 Partial Flight Manual*, K. T. Hutchinson, Calspan Document WI-056-NF16D-0071, Supplement 6, August 18, 1998.

6. *Flying Qualities Course Objectives*, USAF Test Pilot School, Edwards AFB, California. 30 March 1998.

This page intentionally left blank.

# APPENDIX A

# AIRCRAFT CONFIGURATIONS

This page intentionally left blank.

# AIRCRAFT CONFIGURATIONS

## BASELINE AIRCRAFT (HAFA 1 AND HAFA 2) CONFIGURATIONS

The following transfer functions describe the lower order equivalent system (LOES) matching model and control anticipation parameter (CAP) values derived from the Variable Stability In-Flight Simulator Test Aircraft (VISTA) flight step, and frequency responses (Figures A1 and A2) for HAFA 1 and HAFA 2 aircraft, where:

$$\frac{q_{loes}}{\delta_{DES}} = \frac{(K)(T_{\theta 2}s + 1)e^{-\tau_d s}}{\left(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2\right)}$$

$$CAP = \left(\omega_{sp}^2\right) / \left(\left(V_{T_o} / g\right) / T_{\theta 2}\right)$$

LEVEL 1 (300 knots at 15,000 feet, $V_{to}$ = 626.72 feet/sec) (Figure A1)

$$\frac{q_{loes}}{\delta_{DES}} = \frac{(18.998)(0.65s + 1)e^{-0.156s}}{\left(s^2 + 2(0.7)(4.64)s + 4.64^2\right)}$$

CAP=0.718 sec$^{-2}$

LEVEL 2 (300 knots at 15,000 feet, $V_{to}$ = 626.72 feet/sec) (Figure A2)

$$\frac{q_{loes}}{\delta_{DES}} = \frac{(21.816)(0.65s + 1)e^{-0.156s}}{\left(s^2 + 2(0.654)(1.8)s + 1.8^2\right)}$$

CAP=0.108 sec$^{-2}$

The following transfer functions describe the LOES matching model and CAP values derived from VISTA flight step and frequency responses (Figures A3 and A4).

LEVEL 1 (300 knots at 15,000 feet, $V_{to}$ = 626.72 feet/sec) (Figure A3)

$$\frac{q_{loes}}{\delta_{DES}} = \frac{(17.0)(0.65s + 1)e^{-0.124s}}{\left(s^2 + 2(0.7)(5.2)s + 5.2^2\right)}$$

CAP=0.902 sec$^{-2}$

LEVEL 2 (300 knots at 15,000 feet, $V_{to}$ = 626.72 feet/sec) (Figure A4)

$$\frac{q_{loes}}{\delta_{DES}} = \frac{(21.0)(0.65s + 1)e^{-0.056s}}{\left(s^2 + 2(0.75)(2.0)s + 2.0^2\right)}$$

CAP=0.130 sec$^{-2}$

## TEST CONFIGURATIONS (A, B, AND C)

Figures A5 through A7 show diagrams of the three test configurations (A, B, and C, respectively) used during the HAVE FILTER test program.

A 60 degrees per second rate limit was inside the feedback loop. The software rate limiter (SWRL) was simply a software selectable rate limiter placed on the pilot command (outside the feedback loop) to protect the simulated actuator from rate limiting. The nonlinear rate limiter pre-filter (RLPF) algorithm had a software selectable threshold setting and was placed in front of the SWRL. The RLPF attempted to minimize and/or remove any phase lag introduced by the SWRL.

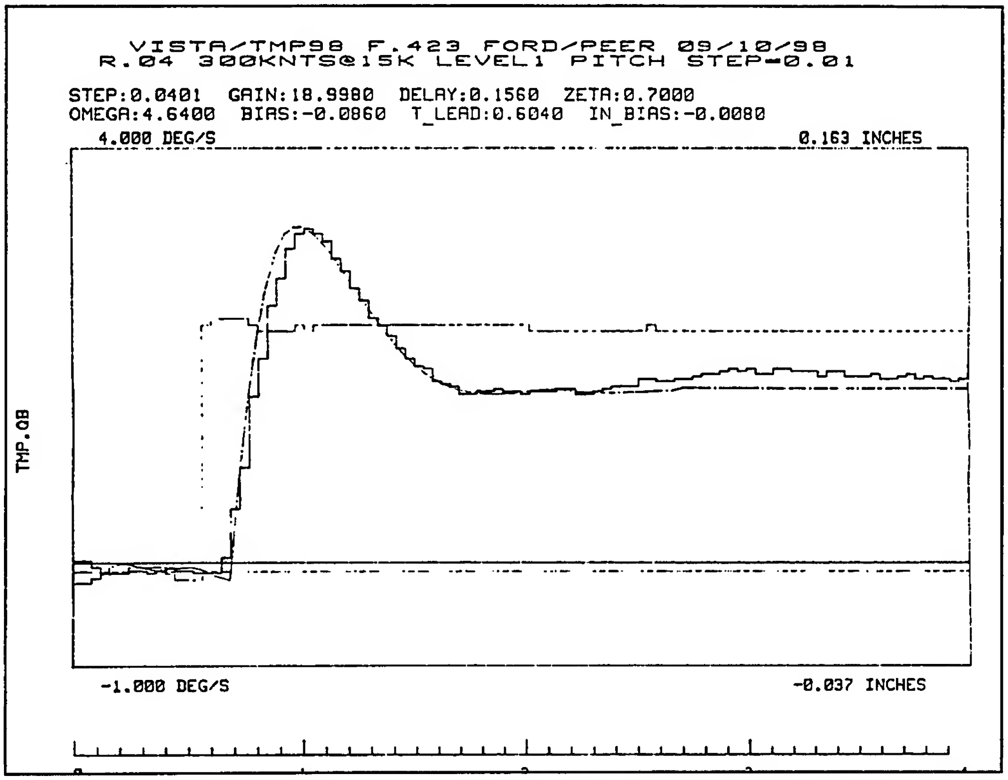


Figure A1 Time-History Matching of Lower Order Equivalent System and Flight Data (Level 1 Aircraft)

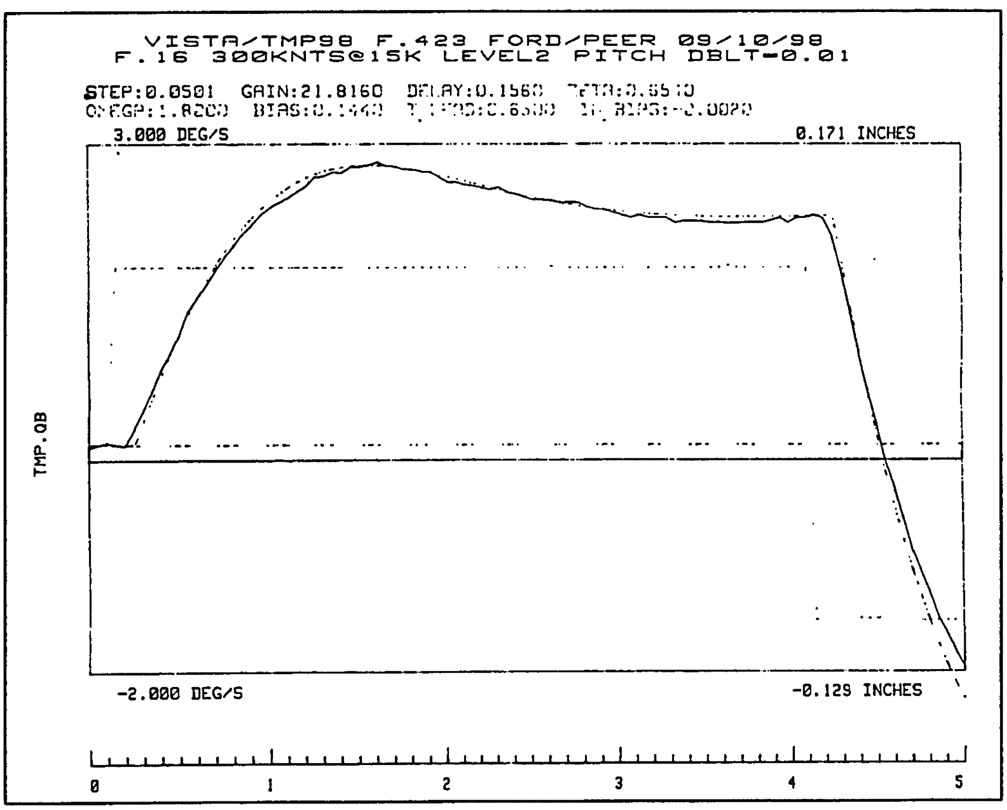


Figure A2 Time-History Matching of Lower Order Equivalent System and Flight Data (Level 2 Aircraft)

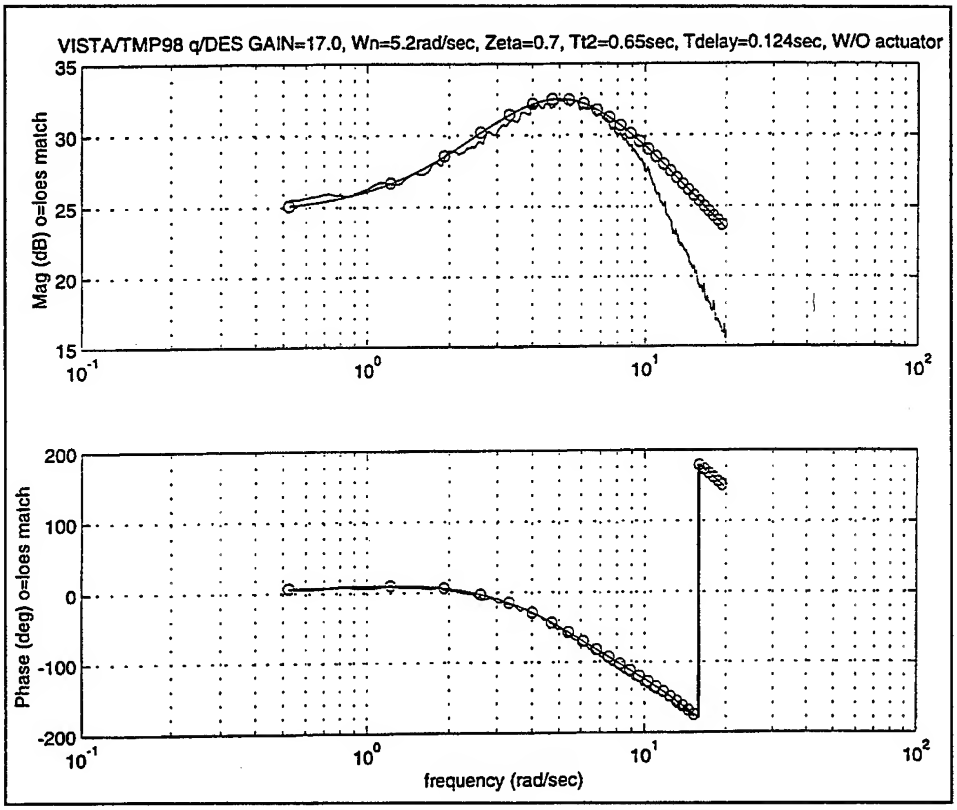


Figure A3 Frequency Matching of Lower Order Equivalent System and Flight Data (Level 1 Aircraft)

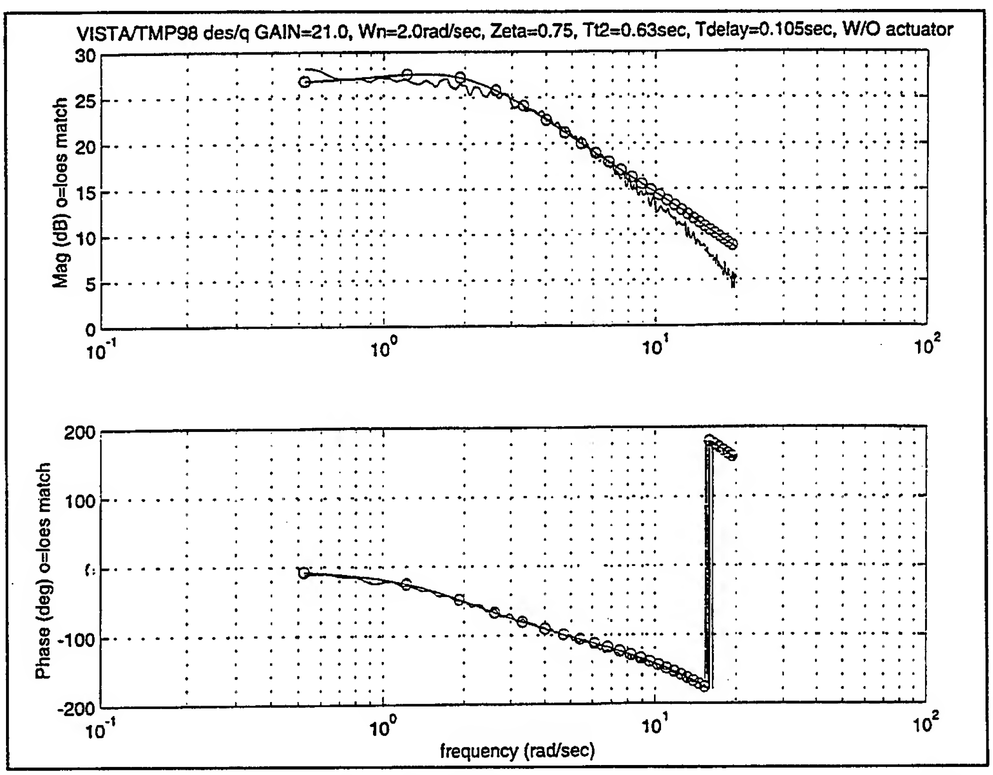


Figure A4 Frequency Matching of Lower Order Equivalent System and Flight Data (Level 2 Aircraft)

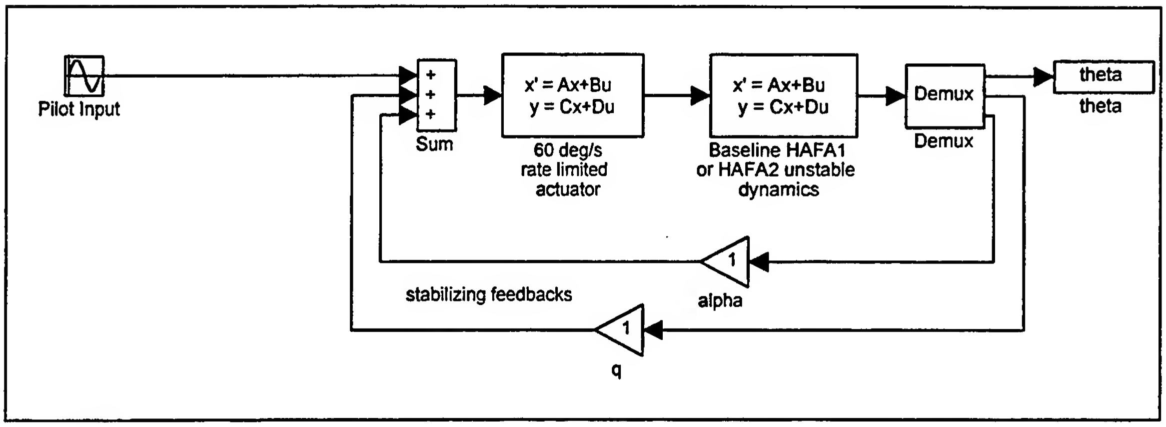


Figure A5 Configuration A (Baseline Aircraft)

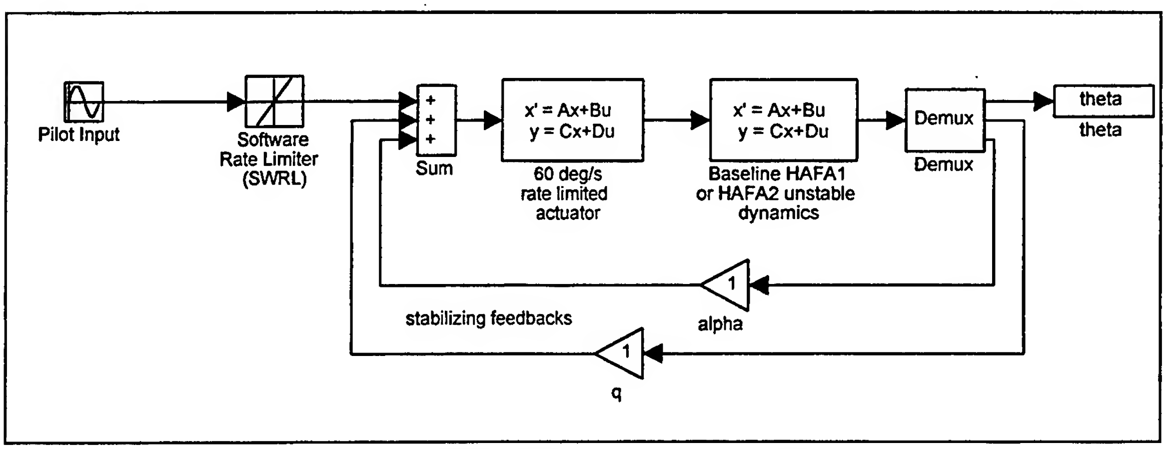


Figure A6 Configuration B (Baseline plus Software Rate Limiter)

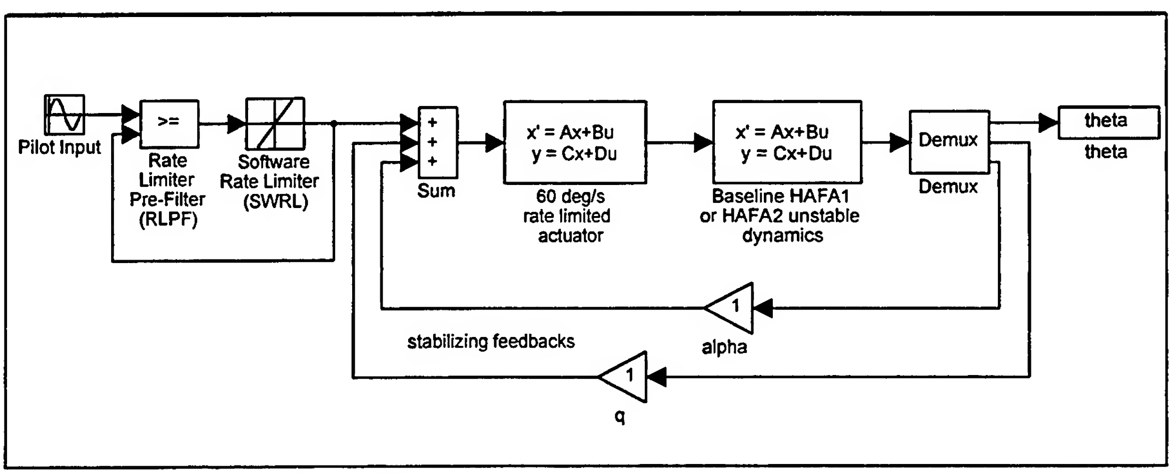


Figure A7 Configuration C (Baseline plus Software Rate Limiter plus Rate Limiter Pre-Filter)

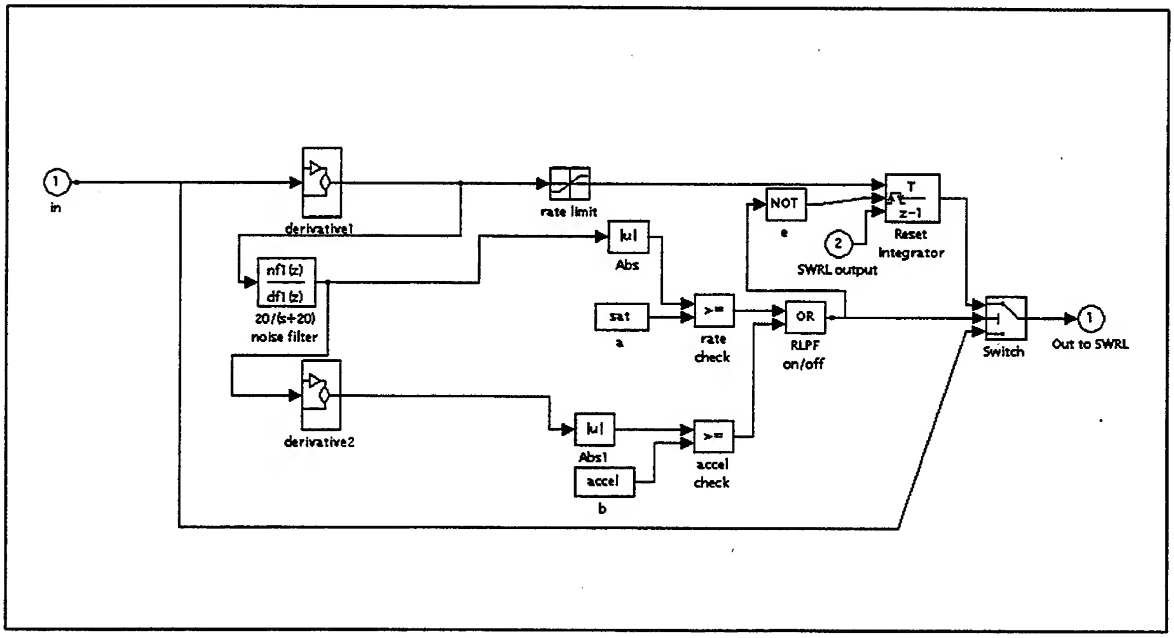


Figure A8 Rate Limiter Pre-Filter Logic

This page intentionally left blank.

# APPENDIX B

# PILOT RATINGS, COMMENTS, AND RATING SCALES

This page intentionally left blank.

# PILOT RATINGS, COMMENTS, AND RATING SCALES

<u>**LEGEND**</u>

**Test Point: XXX** - refers to the numbers in the test matrix found in Table 3, Test and Evaluation section.

**Pilot/Flight Number** (Appendix C, Flight Log)

**Phase Number**: Pilot-Induced Oscillation Tendency Rating (PIOR), Departure Status, Pilot Comments

**Phase Number**: PIOR, Cooper-Harper Rating (CHR), Departure Status, Pilot Comments

**Test Point: 100**

Chapa/425

Ph II: 6 **DEPARTURE** - "Divergent departure?"

Ph III: 5/10 **DEPARTURE** - "Twitchy, coupling with it – big pull → Trip"

Chapa/431

Ph I: "Good initial response – then hangup → osc → dep"

Ph II: 5 **DEPARTURE** - "Very responsive initially"

Ph III: 5/10 **DEPARTURE** - "A little twitchy initial response w/ bobble, but it goes where I want it → easy to couple/osc. I like initial response trip → dep on big pull."

Letourneau/427

Ph I: "Much more sensitive response in pitch than [281]. Pitch bobbles during pitch captures."

Ph II: 4 **NO DEPARTURE** - "Had a sensation that it almost departed in negative $n_z$ right at the end of the task. However, remained bounded."

Ph III: 3/5 **NO DEPARTURE** - "Fine tracking sensitivity made for undesirable motions that compromised task performance. Fine tracking more difficult due to initial pitch response sensitivity. Magnitude of undesirable motions during fine tracking caused adequate criteria to be met."

Letourneau/432

Ph I: "Lot more touchy – quick pitch rate buildup – difficult to arrest."

Ph II: 5 **DEPARTURE** - "Quickly growing oscillation."

Ph III: 5/10 **DEPARTURE** - "Very difficult to arrest oscillations on gross acquisition – eventually departed. Can feel it wanting to go – lots of pilot compensation."

Parker/428

Ph II: 5 - **DEPARTURE**

Ph III: 4/4 **NO DEPARTURE** - "[Slowly decaying oscillations] wasted valuable tracking time – Difficult to track precisely. Oscillations were damped with effort which distracted from the task – i.e. workload increased."

Parker/433

Ph II: 6 - **DEPARTURE**

Ph III: 4/4 **NO DEPARTURE** - "Damped on fine track, but it seemed on one occasion to be about to depart – huge q_dot excursion, saved by going out of loop. Suspect this as being on a tight rope, could go any time."

**Test Point: 120**

Chapa/426

Ph II: 5 **DEPARTURE**

Ph III: 5/10 **DEPARTURE -** "Nice initial response, but bobble/coupling."

Letourneau/430

Ph I: "Responsive but hard to pitch capture."

Ph II: 5 **DEPARTURE -** "Growing oscillations – felt responsive and in phase right up to departure – good departure – lots of roll coupling in task."

Ph III: 3/4 **NO DEPARTURE -** "Quite a bit of undesired motions due to sense of neutral stability. Definite task degradation. Good fine tracking – good initial pitch response – causes gross overshoots – very light stick forces for initial pitch motions – felt almost neutral stable in pitch."

Parker/429

Ph II: 5 **DEPARTURE**

Ph III: 3/4 **NO DEPARTURE -** "Fairly precise (quick), a little loose (bobbly). Not too bad."

**Test Point: 121**

Chapa/426

Ph II: 5 **DEPARTURE**

Ph III: 6/10 **DEPARTURE -** "Very response, but easily induced oscillations"

Letourneau/427

Ph I: "Pitch sensitivity, 1 o/s on pitch captures"

Ph II: 3 **NO DEPARTURE -** "Bounded motion – initial pitch rate response a little fast."

Ph III: 3/5 **NO DEPARTURE -** "Sensitive in pitch – The fine tracking motions compromise task performance – need to back out slightly to damp out. Pitch bobble during fine tracking – overshoots on gross acquisition – too much pitch bobble to meet desired criteria – working hard to keep adequate criteria."

Parker/428

Ph II: 4 **NO DEPARTURE -** "Large amplitude corrections invoked greater rates of overshoots"

Ph III: **INCONCLUSIVE** "Never managed to stabilize the pipper on tgt for more than a second. Generally bounded PIO (small amplitude) – moderate compensation."

**Test Point: 140**

Chapa/426

Ph II: 5 **DEPARTURE**

Ph III: 5/10 **DEPARTURE -** "A little bobble, but good initial response – good initial response, but bobbles/PIO having to back out, PIO → Dep on big pull."

Letourneau/430

Ph I: "Very good initial pitch response – better pitch capture ability than [151].

Ph II: 5 **DEPARTURE -** "Not even bang-bang at departure – felt divergent and valid departure."

**Test Point: 140 (Concluded)**

Ph III: 3/4 **NO DEPARTURE** - "Some pitch bobble right after gross acquisition. Very sensitive in pitch, but fine tracking not that difficult. Not rock steady in fine track, but workable."

Parker/429

Ph II: 5 **DEPARTURE**

Ph III: 4/5 **NO DEPARTURE** - "Erratic, oversensitive, difficult to be smooth."

**Test Point: 141**

Chapa/426

Ph II: 4 **NO DEPARTURE** - "Not responding to my input at times, don't like the response"

Ph III: 4/5 **NO DEPARTURE** - "Bobble, but response not too terrible – good initial response, a little oscillation – lots of little bobbles – performance deemed desired, but objectionable HQ deficiencies (bobbles)."

Chapa/431

Ph II: 5 **DEPARTURE** - "Twitchy"

Ph III: 4/5 **NO DEPARTURE** - "Pretty good initial response, then it hangs up – a little coupling at top (of big pulls), a little sluggish on bit pull → osc, able to stop it."

Letourneau/430

Ph I: "Very pitch sensitive – hard to arrest – lots of bobble."

Ph II: 4 **DEPARTURE** - "Very responsive, felt like a good departure – could feel the saturation."

Ph III: 4/6 **NO DEPARTURE** - "Little bobble – oscillations after gross acquisition – need to back out. Lots of overshoots on gross acquisition. Small improvement over [161]. Out of phase on gross acquisition."

Letourneau/432

Ph I: "Fast pitch rate buildup – twitchy."

Ph II: 3 **NO DEPARTURE** - "Bang-bang achieved. Degrading motions. Can feel changing pitch rates – initially responds to commands up to a point and then resists."

Ph III: 3/5 **NO DEPARTURE** - "Stepped buildup - causes degrading motions and unpredictability. Too much bobble while chasing the target. Stepped pitch rate buildup. Little twitchy."

Parker/429

Ph II: 5 **NO DEPARTURE**

Ph III: 4/6 **NO DEPARTURE** - "Too sensitive with obvious rate limiting. Not pleasant (but slightly better than [161]."

Parker/433

Ph II: 5 **DEPARTURE**

Ph III: 3/3 **NO DEPARTURE** - "A little loose – responsive but well damped during fine tracking. Nice."

**Test Point: 150**

Chapa/426

Ph II: 5 **DEPARTURE**

Ph III: 5/10 **DEPARTURE** - "Liked general response to small inputs – bobble, coupling."

Letourneau/430

Ph I: "Good initial pitch response."

Ph II: 4 **DEPARTURE**

Ph III: 4/6 **NO DEPARTURE** - "Pitch bobble during fine tracking. Backing out of loop to stop oscillations. Fine tracking difficult – out of phase on fine tracking. Overshoots on gross acq. – easy to over-control."

Parker/429

Ph II: **INCONCLUSIVE** - "Pitch rate slightly variable"

Ph III: 4/5 **NO DEPARTURE** - "The overall feel was loose system. Difficult to predict. Pipper placement was difficult to hold steady."

**Test Point: 151**

Chapa/426

Ph II: 4 **NO DEPARTURE** - "Strange response, and at times no control, i.e. the input was in with no aircraft response, but no departure

Ph III: **INCONCLUSIVE** - "A little bobble, very hard to control airplane – mind of its own, sucks."

Chapa/431

Ph II: 3 **NO DEPARTURE** - "A little non-responsiveness at times, but not divergent"

Ph III: 4/4 **NO DEPARTURE** - "Nice initial response, not too much bobbling, a little bobble after capture, coupling/PIO after big pull, had to back out – overall good, but a few minor exceptions."

Letourneau/430

Ph I: "Very responsive in pitch – difficult to fine track."

Ph II: **INCONCLUSIVE** - "Felt like a good departure – growing oscillation – felt like controls saturated."

Ph III: 3/5 **NO DEPARTURE** - "Pitch bobble degraded task performance. Bad pitch bobble. More squirrelly trying to settle on fine tracking (than [251]). Could not maintain desired criteria due to bobble."

Letourneau/432

Ph I: "Slower pitch rate buildup than [160] – still sensitive – difficult to arrest pitch rate smoothly."

Ph II: 4 **NO DEPARTURE** - "Can feel changing pitch rate responses during portions of HQDT. Prevents departures as aircraft initially ignores pilot commands – appeared as a large delay – would cycle in and out of the pitch response delay."

Ph III: 4/8 **NO DEPARTURE** - "Twitchiness around fine tracking. Controllability in question – especially when aircraft reacting opposite to inputs. Intermittent delays in aircraft response. Made it very unpredictable – sense that system was helping to prevent a departure. Mixed with roll task seems to unmask same controllability issues not present in phase 2."

Parker/429

Ph II: 4 **NO DEPARTURE**

**Test Point 151 (Concluded)**

Ph III: 4/5 **NO DEPARTURE** - "Very springy/oscillatory. Lots of overshoots – too loose. Hard work getting adequate."

Parker/433

Ph II: 6 **DEPARTURE**

Ph III: 4/4 **NO DEPARTURE** - "Gross acquisition, 2 to 3 overshoots every time. Fairly well damped, enabling fine tracking. Needs improvement."

**Test Point: 160**

Chapa/426

Ph II: 4 **NO DEPARTURE** - "Carnival ride, loose but not divergent."

Ph III: **INCONCLUSIVE** - "Bobbling a little."

Chapa/431

Ph II: 4 **NO DEPARTURE**

Ph III: 4/6 **NO DEPARTURE** - "Crisp initial response, but easy to couple, bobbling/coupling – not real desirable, coupling – had to back out, difficult to capture large pull → osc."

Letourneau/430

Ph I: "Good onset of pitch rate – bobble on tight control."

Ph II: **INCONCLUSIVE** - "Bang-bang achieved – felt like a good departure."

Ph III: 5/10 **DEPARTURE** - "PIO after gross acquisition – need to back out. Bobble on fine tracking. Exponentially worse with more aggressive maneuvering."

Letourneau/432

Ph I: "Much more responsive, very sensitive – fast pitch rate buildup difficult to arrest."

Ph II: **INCONCLUSIVE** - "Stop-stop achieved – very responsive – bounded oscillation."

Ph III: 5/10 **DEPARTURE** - "Very twitchy. Very sensitive pitch response. Pitch rate buildup got out of control."

Parker/429

Ph II: 3 **NO DEPARTURE**

Ph III: 3/3 **NO DEPARTURE** - "Precise, small pitch bobbles but desired met. Fine tracking easy, gross acq not so good , but desired. 2 or 3 overshoots."

Parker/433

Ph II: **INCONCLUSIVE**

Ph III: 4/6 **NO DEPARTURE** - "Almost impossible to damp whilst in the loop. Hard work."

**Test Point: 161**

Chapa/426

Ph II: **INCONCLUSIVE**

Ph III: 4/6 **NO DEPARTURE** - "Sometimes the aircraft response doesn't match inputs. Nice initial response, but some bobble/coupling – lots of bobble → PIO, uncommanded response, sluggish, doing its own thing at times, large input → not much response."

**Test Point 161 (Concluded)**

Chapa/431

Ph I: "Good initial response – able to stop it – I like it."

Ph II: 3 **NO DEPARTURE** - "Some uncommanded motion (no response)."

Ph III: 4/5 **NO DEPARTURE** - "A little bobble after good initial response – fair amount of bobbling, slow on <u>big pull</u> and then undesirable – lack of response, lots of bobble."

Letourneau/430

Ph I: "Fast pitch ramp-up difficult to arrest."

Ph II: **INCONCLUSIVE** - "Bang-bang achieved – felt like it was hanging in there but good departure."

Ph III: 4/8 **NO DEPARTURE** - "Bounded oscillations throughout – required backing out. Not easy to control. Lots of pitch rate inertia. Horrible configuration. Feels like changing flight control gains."

Letourneau/432

Ph I: "Little touchy."

Ph II: 4 **NO DEPARTURE** - "Initially good pitch rate buildup – stop to stop. Can occasionally feel pitch response delays – sense of keeping oscillations bounded."

Ph III: 4/8 **NO DEPARTURE** - "Touchy in fine tracking – sense that variable pitch rates were keeping oscillations bounded. Good initial response – tough to arrest. Controllability in question as pitch rate response changes throughout maneuver – however – while it seems the aircraft is fighting my inputs on occasion there is a sense that it is helping to prevent a departure by arresting a pitch rate prior to honoring a command."

Parker/429

Ph II: **INCONCLUSIVE** - "Very loose/unpredictable. Rate limiting. Over sensitive."

Ph III: 4/6 **NO DEPARTURE** - "You could feel rate limiting on this one. Pitch rate was not linear to input. Made it difficult to be accurate. Hard work."

Parker/433

Ph II: 4 **NO DEPARTURE** - "Lots of rate limiting. Questionable control."

Ph III: 4/5 **NO DEPARTURE** - "Predictability was the biggest issue. Although it did not depart, it lacked the precision needed to attain desired results."

**Test Point: 180**

Chapa/425

Ph II: **INCONCLUSIVE**

Ph III: 3/4 **NO DEPARTURE** - "A little bobble, overshoot, PIO (multiple) – hard to back out some."

Letourneau/427

Ph I: "Feels like a lead filter. Pitch rate buildup is faster at input then at steady-state."

Ph II: 4 **NO DEPARTURE** - "Extreme initial sensitivity caused a small bounded oscillation."

Ph III: 3/4 **NO DEPARTURE** - "Gross acquisition overshoots. Initial input sensitivity compromised task performance. Initial sensitivity required backing off aggressiveness to meet desired performance (on tape review it appeared to be adequate performance)."

Letourneau/432

Ph I: "Touch pitch response – bobbly – hard to arrest."

Ph II: 4 **NO DEPARTURE** - "Stop-to-stop. Bounded oscillation."

**Test Point 180 (Concluded)**

Ph III: 4/8 **NO DEPARTURE** - "Feel motions grow in amplitude and have to back out to keep things bounded – never quite dampens out. Sensitive in initial acquisition. Controllability in question. Had to back out on several occasions. Roll task seems to unmask problems not inherent in phase 2."

Parker/428

Ph II: **INCONCLUSIVE**

Ph III: 3/3 **NO DEPARTURE** - "Small annoying pitch bobbles – present with aggressive tracking – Gross acquisition was difficult to achieve without at least one or two overshoots. Fine acquisition was better but not as precise as I would have liked (Desired)."

Parker/433

Ph II: 3 **NO DEPARTURE**

Ph III: 4/4 **NO DEPARTURE** - "Too sensitive and "springy" for fine track, otherwise OK."

**Test Point: 181**

Chapa/425

Ph II: **INCONCLUSIVE**

Ph III: **INCONCLUSIVE** - "Pitch rate buildup (non-linear response), sluggish, bobbles – do not like response, can't do anything with it – sucks."

Chapa/431

Ph II: 4 **NO DEPARTURE** - "Something uncommanded going on there."

Ph III: 4/8 **NO DEPARTURE** - "Crisp initial response, the buildup to hangup of uncommanded nature – big overshoot, uncommanded no response – had to back out of loop then osc, initial pull good, but shortly thereafter not always responsive – very undesirable."

Letourneau/427

Ph I: "Very sensitive in pitch. Lots of bobble – difficult to pitch capture."

Ph II: **INCONCLUSIVE** - "Growing oscillation with bang-bang technique. Large delay in pitch onset rate and then fast ramp up."

Ph III: 4/7 **NO DEPARTURE** - "Delay in pitch rate onset and then steep ramp up caused large overshoots in gross acquisition. Extreme pilot compensation minimized the magnitude of the overshoot. Bounded oscillation during fine tracking. Felt it was due to the delay and then steep ramp up of pitch rate. Controllability not in question, but extreme pilot compensation was unable to meet adequate criteria."

Letourneau/432

Ph I: "Quick pitch rate buildup – hard to arrest – some bobble."

Ph II: 3 **NO DEPARTURE** - "Can feel changing pitch rate responses – almost a 1.5 second delay at times before responding to commands and nearly instantaneous at others – seemed to prevent a bounded oscillation."

Ph III: 4/8 **NO DEPARTURE** - "Sense of bounded oscillation during most acquisitions requiring backing out of system. Good initial acquisition. Fighting my inputs – easily saturated. Extreme pilot compensation, trying to guess when pitch rates would change. Roll task helped unmask some controllability issues. Felt like it almost departed towards the end of the task, but compensation prevented it."

**Test Point: 181 (Concluded)**

Parker/428

Ph II: **INCONCLUSIVE**

Ph III: 4/8 **NO DEPARTURE** - "Pitch control extremely erratic, Q was oscillatory – major problem during tracking. Predictability was very poor. Overshoots were large amplitude. Not good."

Parker/433

Ph II: 4 **NO DEPARTURE**

Ph III: 3/6 **NO DEPARTURE** - "Too unpredictable. Q_dot varied too much. Obvious rate limiting. When not in rate limit, system was too loose."

**Test Point: 200**

Chapa/425

Ph II: **INCONCLUSIVE** - "Hanging together."

Ph III: 2/3 **NO DEPARTURE** - "Little overshoots, but able to stop it – I like the response, handling very well, little coupling, nice response on big pull – Liked it, but sometimes an overshoot that was stoppable."

Chapa/431

Ph II: 4 **NO DEPARTURE** - "Very big overshoots in up direction."

Ph III: 3/5 **NO DEPARTURE** - "Sluggish initial response – pitch rate buildup – overshoots – dampens OK after pull, a little PIO trying to stop pitch rate, overshoot able to stop."

Letourneau/427

Ph I: "Small delay on pitch input, but ramps up nicely. Well behaved."

Ph II: 3 **NO DEPARTURE** - "Some undesirable motions but aircraft responding well. Faster pitch rate buildup than [221] causes larger overshoots. Bang-bang achieved with no bounded oscillations."

Ph III: 2/3 **NO DEPARTURE** - "Only small undesired motions during fine tracking. 2 overshoots on gross acquisition. Fine tracking much easier in this configuration. Well behaved and predictable."

Letourneau/432

Ph I: "Little more responsive than [261] – still feels well behaved."

Ph II: 3 **NO DEPARTURE** - "Stop-to-stop. Aircraft responds very nicely."

Ph III: 2/3 **NO DEPARTURE** - "Solid in fine tracking. Gross acquisition simple. Just about right. Liked it best."

Parker/428

Ph II: 4 **NO DEPARTURE**

Ph III: 2/3 **NO DEPARTURE** - "Better. Damped somewhat, but not perfect."

Parker/433

Ph II: 4 **NO DEPARTURE**

Ph III: 3/3 **NO DEPARTURE** - "Too sluggish, but helped with the desired score. Any larger K_task would probably degrade the HQ of this system. Slightly bobbly when in tight loop."

**Test Point: 220**

Chapa/425

Ph II: **INCONCLUSIVE**

Ph III: 2/3 **NO DEPARTURE** - "Fairly sluggish, no residual coupling after gross acq, bobble (a little) – big acq liked response."

Letourneau/427

Ph I: "Very similar to [250]. Little less response in pitch."

Ph II: 3 **NO DEPARTURE** - "Little slow to respond – stick motion – stop to stop – aircraft motion was not quick, but not a degrading lag. Not a bounded oscillation."

Ph III: 3/5 **NO DEPARTURE** - "Sluggishness made for undesirable motions, but no PIO tendency. Objectionably sluggish response. Made getting to a fine tracking solution difficult. Once there it was a stable platform."

Parker/428

Ph II: 5 **NO DEPARTURE** - "Divergent. Task finished before departure – probably would have departed if the task was longer."

Ph III: 4/4 **NO DEPARTURE** - "Oscillations occurred throughout which were more prevalent with aggressive/large amplitude inputs."

**Test Point: 221**

Chapa/425

Ph II: 3 **NO DEPARTURE** - "Some growth in bounded osc, but arrested back into non-divergent tracking."

Ph III: 2/4 **NO DEPARTURE** - "Pitch rate buildup, a little sluggish but stopped on a dime, a little unpredictable, but able to stop it nicely on big pull."

Letourneau/427

Ph I: "Pretty nice airplane, very responsive."

Ph II: **INCONCLUSIVE** - "Reached bang bang early on. Aircraft extremely responsive, no tendency to PIO."

Ph III: 2/3 **NO DEPARTURE** - "Small overshoots on gross acquisition but did not compromise task performance. Very well behaved, best configuration so far during the flight. Nice initial response and steady state response on gross acquisition."

Parker/428

Ph II: 3 **NO DEPARTURE**

Ph III: 2/3 **NO DEPARTURE** - "Minor bobbles. Controllable, but not acceptable. Max aggression still achieved desired – video suggested only adequate [rated as desired]."

**Test Point: 240**

Chapa/426

Ph II: 3 **NO DEPARTURE** - "Seems to be hanging pretty good – not much undesirable"

Ph III: **INCONCLUSIVE** - "A little sluggish initial response, a little bobble – I like the response for the most part."

Chapa/431

Ph II: **INCONCLUSIVE**

Ph III: 4/5 **NO DEPARTURE** - "A little sluggish initial response, some small osc in fine tracking, some coupling."

**Test Point: 240 (Concluded)**

Letourneau/430

Ph I: "Slower pitch rate ramp-up."

Ph II: **INCONCLUSIVE** - "Bang-bang achieved. Not as responsive in negative pitch rate."

Ph III: 3/4 **NO DEPARTURE** - "Minor bobble on fine tracking. Solid fine tracking. Pretty stable. Slower initial response."

Letourneau/432

Ph I: "Sluggish, slow pitch buildup."

Ph II: 3 **INCONCLUSIVE** - "Bang-bang achieved – behaved well."

Ph III: 3/5 **NO DEPARTURE** - "Little twitchy in fine tracking. Little sluggish – slow ramp up in pitch rate. Sluggish response made meeting desired criteria not possible."

Parker/429

Ph II: 4 **NO DEPARTURE**

Ph III: 3/3 **NO DEPARTURE** - "Nice. Fine tracking a bit bobbly – Gross acquisition – nice, damped, easy to predict."

Parker/433

Ph II: **INCONCLUSIVE**

Ph III: 4/5 **NO DEPARTURE** - "Difficult to accurately predict gross acquisition. Fine tracking purity was spoiled by bobbles (lots of them)."

**Test Point: 241**

Chapa/426

Ph II: 3 **NO DEPARTURE** - "Wasn't quite as responsive as I would have liked."

Ph III: 3/4 **NO DEPARTURE** - "Fairly sluggish on initial pull w/ pitch rate buildup – a little PIO, bug overshoots w/ some residual oscillations, much of the tracking was fine."

Chapa/431

Ph II: **INCONCLUSIVE** - "Sluggish initial response to large overshoots"

Ph III: 3/6 **NO DEPARTURE** - "Big overshoots on pitch capture w/ pitch rate buildup – phase I. Sluggish initial response, can't stop airplane where I want it."

Letourneau/430

Ph I: "Slower pitch rate buildup – more solid feel."

Ph II: **INCONCLUSIVE**

Ph III: 2/3 **NO DEPARTURE** - "Minimal bobble. Initial pitch response a touch sluggish – helps to minimize overshoots. Minimal bobble – tracks real nice. Felt like a heavier stick."

Letourneau/432

Ph I: "Slower but steady pitch buildup. More deadbeat."

Ph II: 3 **NO DEPARTURE** - "Well behaved. Stop to stop."

Ph III: 3/4 **NO DEPARTURE** - "Undesirable motions during fine track while the target was moving degraded performance. Nice in gross acquisition."

Parker/429

Ph II: **INCONCLUSIVE**

Ph III: **INCONCLUSIVE** - "Departure – quite likely. Very difficult to track with any precision."

**Test Point: 241 (Concluded)**

Parker/433

Ph II: **INCONCLUSIVE**

Ph III: 4/6 **NO DEPARTURE** - "Very sluggish. Difficult to maintain zero error for more than 1/4 second due to bobbles."

**Test Point: 250**

Chapa/425

Ph II: **INCONCLUSIVE**

Ph III: 3/4 **NO DEPARTURE** - "Very sluggish, big delay – No residual bobble after gross acq, but not real responsive, a little unpredictable."

Letourneau/427

Ph I: "Small lag in pitch response, but steady pitch rate."

Ph II: 3 **NO DEPARTURE** - "Very well behaved, aircraft responded very quickly to inputs. Stich motion achieved stop-to-stop by middle of task with no degrading lag."

Ph III: 3/4 **NO DEPARTURE** - "Much better damped than [180]. Pipper moves much less during fine tracking. Overshoots on gross acquisition. Predictable aircraft."

Parker/428

Ph II: **INCONCLUSIVE**

Ph III: 4/5 **NO DEPARTURE** - "Adequate, high workload."

**Test Point: 251**

Chapa/426

Ph II: 3 **NO DEPARTURE** - "Sluggish response, but hung together."

Ph III: **INCONCLUSIVE** - "Pitch rate buildup, sluggish initial response, good damping on large inputs, hard to make the thing do what I want in pitch at times."

Chapa/431

Ph I: "Big, huge overshoot, sluggish response."

Ph II: 4 **NO DEPARTURE** - "Sluggish, big overshoots, slow turn around."

Ph III: 3/5 **NO DEPARTURE** - "Sluggish initial response, damps well, very sluggish, a little bobble after big overshoot on big pull – able to stop it."

Letourneau/430

Ph I: "Slower pitch rate buildup – hard to arrest once going."

Ph II: **INCONCLUSIVE** - "Bang-bang during HQDT. Oscillations growing – left with impression of impending departure."

Ph III: 2/3 **NO DEPARTURE** - "Solid in fine track. Initial acquisition good. Little bit of roll coupling from turbulence."

Letourneau/432

Ph I: "Slower pitch rate buildup – easy to arrest."

Ph II: 3 **NO DEPARTURE** - "Pitch rate buildup feel [parabolic/quadratic] – good response throughout – stop-to-stop."

Ph III: 2/3 **NO DEPARTURE** - "Steady tracking – deadbeat during fine tracking. Well behaved – very nice. Easily arrested pitch rate – deadbeat. Predictable behavior."

**Test Point: 251 (Concluded)**

Parker/429

Ph II: **INCONCLUSIVE**

Ph III: 3/4 **NO DEPARTURE -** "Sluggish pitch with low predictability."

Parker/433

Ph II: 3 **NO DEPARTURE**

Ph III: 3/3 **NO DEPARTURE -** "Well damped. Predictable and nice (relatively speaking)."

**Test Point: 260**

Chapa/431

Ph II: 4 **NO DEPARTURE -** "Sluggish, slow to turn around, big overshoots."

Ph III: 3/5 **NO DEPARTURE -** "Bit overshoots – not real crisp – pitch rate buildup, then hang up (Ph I) – sluggish initial response, but stops OK. Nice stop on big pull but sluggish initial response."

Letourneau/432

Ph I: "Nice plane. Decent pitch response & buildup. Maybe a touch sensitive in fine tracking."

Ph II: 3 **NO DEPARTURE -** "Stop to stop – well behaved."

Ph III: 2/3 **NO DEPARTURE -** "Well behaved. Tracks well – fine tracking."

Parker/433

Ph II: 4 **NO DEPARTURE**

Ph III: 3/3 **NO DEPARTURE -** "A little sluggish but helpfully so. Fairly well damped. Nice."

**Test Point: 261**

Chapa/426

Ph II: **INCONCLUSIVE -** "A little sluggish to inputs."

Ph III: **INCONCLUSIVE -** "Pitch rate buildup, unpredictable – a little sluggish on big pulls."

Chapa/431

Ph II: 4 **NO DEPARTURE -** "Very large overshoots, sluggish reversals at top, similar to [281]."

Ph III: 4/5 **NO DEPARTURE -** "Big overshoots, sluggish initially, pitch rate buildup – sluggish initial response → overshoot tendency – osc @ top of big pull, overshoot."

Letourneau/430

Ph I: "Feels nice."

Ph II: **INCONCLUSIVE**

Ph III: 2/3 **NO DEPARTURE -** "Good initial acquisition. Solid fine tracking. Touch sluggish in pitch response. Pitch rate buildup but not very predictable on small gross acquisition."

Letourneau/432

Ph I: "Maybe a little slower pitch rate buildup than [281] – but solid."

Ph II: 3 **NO DEPARTURE -** "Stop to stop – behaving really well – responding as soon as inputs are put in."

Ph III: 2/3 **NO DEPARTURE -** "Like a rock for fine tracking. Easy gross acquisition."

**Test Point: 261 (Concluded)**

Parker/429

Ph II: 3 **NO DEPARTURE**

Ph III: 4/4 **NO DEPARTURE** - "Sluggish with varying q_dot – makes it slightly difficult to predict and track. Worked hard to get a 4."

Parker/433

Ph II: 4 **NO DEPARTURE**

Ph III: 3/3 **NO DEPARTURE** - "Relatively sluggish and damped allowing for desired performance. Nice."

**Test Point: 280**

Chapa/425

Ph II: 3 **NO DEPARTURE** - "A little sluggish, especially on large reversal."

Ph III: 3/4 **NO DEPARTURE** - "Pretty good, a little sluggish, a little PIO on big pull – able to arrest it."

Letourneau/427

Ph II: 4 **NO DEPARTURE** - "Definite bounded oscillation. May have been growing slowly. General sense that it was going to depart but the task ended. Bang-bang achieved."

Ph III: 3/4 **NO DEPARTURE** - "Bobble on gross acquisition. Very subtle motion during fine tracking – aircraft seems to bobble without stick inputs. Fine tracking motions make desired performance difficult but achievable."

Parker/428

Ph II: **INCONCLUSIVE**

**Test Point: 281**

Chapa/425

Ph II: **INCONCLUSIVE**

Ph III: **INCONCLUSIVE**

Chapa/431

Ph II: 4 **NO DEPARTURE** - "Big overshoots, very sluggish."

Ph III: 4/6 **NO DEPARTURE** - "Sluggish initial response – pitch rate buildup – overshoots – harmony poor (roll more responsive) – oscillations on big pull @ top – can't stop aircraft once you get it going."

Letourneau/427

Ph I: "Not as responsive in pitch as [121], lag in the response – motion continues after controls neutralized, more evidence of lag as the motion does not damp out."

Ph II: 4 **NO DEPARTURE** - "Definite bounded oscillations – appears to be due to pitch response lag."

Ph III: 3/4 **NO DEPARTURE** - "Pilot compensation under tight control created an undesirable motion, but the level of compensation required compromised task performance. More sluggish response than [121] makes for better gross acquisition. 2 o/s on gross acquisition. More stable pipper during fine tracking than in [121]."

**Test Point: 281 (Concluded)**

Letourneau/432

Ph I: "Slower pitch rate buildup than [141] – deadbeat – likable."

Ph II: 3 **NO DEPARTURE** - "Steady pitch rate buildup – stop-stop. Pretty good airplane."

Ph III: 2/3 **NO DEPARTURE** - "Solid fine tracking – no objectionable bobble. Maybe a little sluggish overall but good initial response. Able to arrest pitch rates easily on gross acquisition."

Parker/428

Ph II: **INCONCLUSIVE**

Ph III: 4/5 **NO DEPARTURE** - "Bounded, annoying oscillations – Slacked out of the loop a bit to reduce the amplitude of overshoots – adequate performance but high workload."

Parker/433

Ph II: **INCONCLUSIVE**

Ph III: 3/4 **NO DEPARTURE** - "Initial response – too sensitive but damped enough to achieve desired. Generally a tight system on fine tracking."

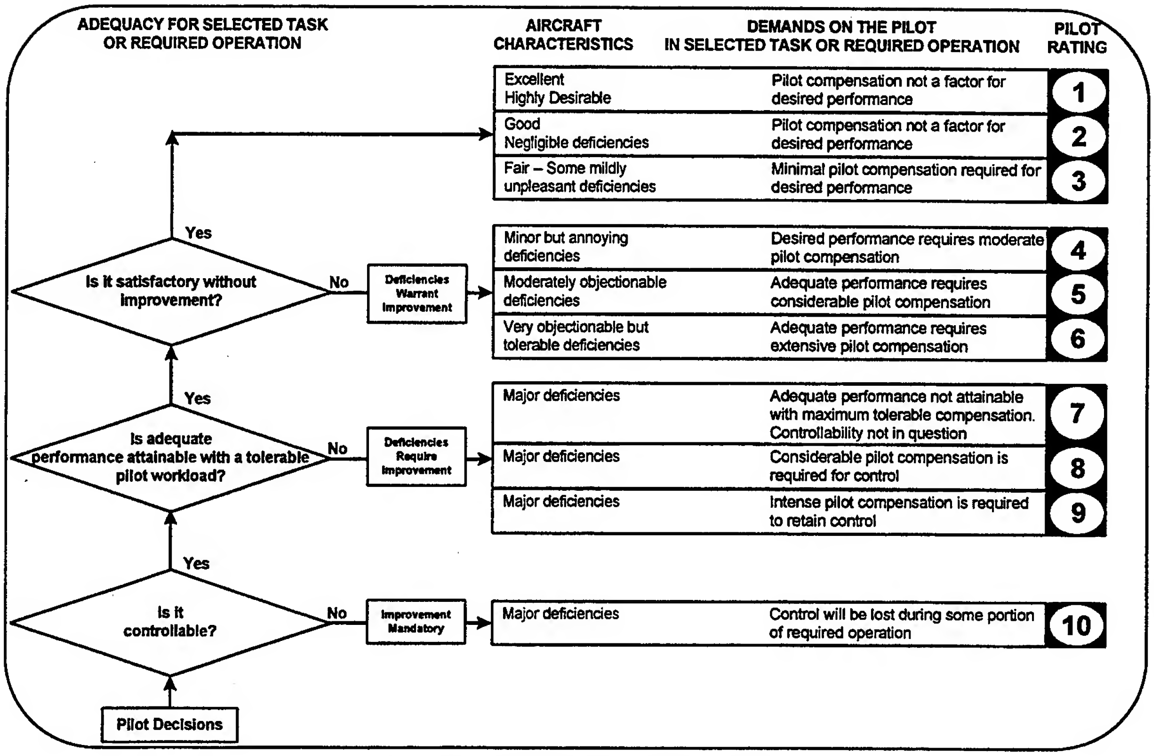


Figure B1 Cooper-Harper Rating Scale

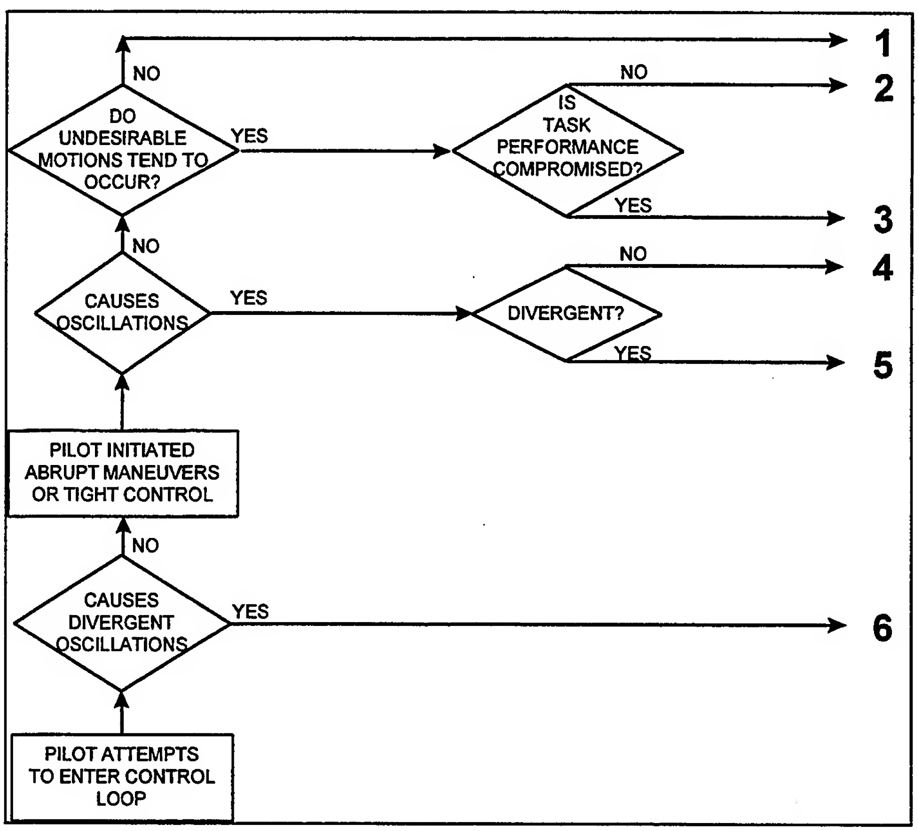


Figure B2 Pilot-Induced Oscillation Tendency Classification

This page intentionally left blank.

# APPENDIX C

# FLIGHT LOG

This page intentionally left blank.

Table C1
FLIGHT LOG

| PROGRAM FLIGHT SUMMARY | | | | |
|---|---|---|---|---|
| FLIGHT NUMBER | DATE/DURATION | EP/SP | TAPE # | RECORD COUNT |
| 421 | 1 SEP 98/1.1 | BALL/PEER | N/A | N/A |
| 422 | 4 SEP 98/1.0 | PEER/BALL | N/A | N/A |
| 423 | 10 SEP 98/1.1 | FORD/PEER | 52 | 25 |
| 424 | 11 SEP 98/1.1 | CHAPA/PEER | 53 | 19 |
| 425 | 12 SEP 98/1.1 | CHAPA/PEER | 55 | 30 |
| 426 | 12 SEP 98/1.1 | CHAPA/PEER | 57 | 35 |
| 427 | 13 SEP 98/1.1 | LETOURNEAU/PEER | 59 | 32 |
| 428 | 13 SEP 98/1.1 | PARKER/PEER | 60 | 31 |
| 429 | 14 SEP 98/1.1 | PARKER/PEER | 61<br>63 | 27<br>28-33 |
| 430 | 14 SEP 98/1.1 | LETOURNEAU/PEER | 62 | 33 |
| 431 | 17 SEP 98/1.2 | CHAPA/PEER | 64 | 39 |
| 432 | 17 SEP 98/1.4 | LETOURNEAU/PEER | 65 | 44 |
| 433 | 18 SEP 98/1.4 | PARKER/PEER | 67 | 44 |

This page intentionally left blank.

# LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

| Abbreviation | Definition | Unit |
|---|---|---|
| AFB | Air Force Base | --- |
| AFFTC | Air Force Flight Test Center | --- |
| AFIT | Air Force Institute of Technology | --- |
| AFRL | Air Force Research Laboratory | --- |
| CAP | Control Anticipation Parameter | --- |
| CHR | Cooper-Harper rating | --- |
| HAFA (1 & 2) | highly-augmented fighter aircraft | --- |
| HQDT | handling qualities during tracking | --- |
| HUD | head-up display | --- |
| in | inch(es) | --- |
| KCAS | knots calibrated airspeed | --- |
| LAMARS | Large Amplitude Multimode Aerospace Simulator | --- |
| LOES | lower order equivalent system | --- |
| lb | pound(s) | --- |
| MFD | multifunction display | --- |
| MOP | measures of performance | --- |
| PDS | programmable display system | --- |
| PIO | pilot-induced oscillation | --- |
| PIOR | PIO tendency rating | --- |
| PTO | participating test organization | --- |
| RAF | Royal Air Force | --- |
| RLPF | rate limiter pre-filter | --- |
| RTO | responsible test organization | --- |
| rad | radian | --- |
| S/N | serial number | --- |
| SWRL | software rate limiter | --- |
| sec | second(s) | --- |
| TPS | Test Pilot School | --- |
| VISTA | Variable Stability In-Flight Simulator Test Aircraft | --- |
| VSS | variable stability system | --- |
| USN | United States Navy | --- |
| USAF | United States Air Force | --- |
| $\omega_{sp}$ | short period natural frequency | rad/sec |

# LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (Concluded)

| Abbreviation | Definition | Unit |
| --- | --- | --- |
| $\zeta_{sp}$ | short period damping ratio | --- |
| $T_{\theta 2}$ | transfer function numerator zero determinant | sec |

# DISTRIBUTION LIST

| Onsite Distribution | Number of Copies | Electronic |
|---|---|---|
| AFFTC/HO<br>305 E Popson Ave<br>Edwards AFB, CA 93524-6595 | 1 | 0 |
| 412 TW/TSTL<br>307 E Popson Ave<br>Edwards AFB, CA 93524-6630 | 3 | 0 |
| 412 TW/TSF<br>195 E Popson Ave, Bldg. 2750<br>Edwards AFB CA 93524-6841 | 3 | 0 |
| USAF TPS<br>220 S Wolfe Ave<br>Edwards AFB CA 93524 | 1 | 1 |
| Capt Michael Chapa<br>416th Combined Test Force<br>Edwards AFB CA 93524 | 2 | 1 |
| Brian Hobbs<br>412 OG/OGX (JSF)<br>Edwards AFB CA 93524 | 2 | 0 |
| Major Kevin Ford<br>USAF TPS<br>220 S Wolfe Ave<br>Edwards AFB CA 93524 | 1 | 0 |
| **Offsite Distribution** | | |
| Defense Technical Information Center<br>DTIC/OMI<br>8725 John L. Kingman Road, Suite 0944<br>Ft Belvoir, VA 22060-6218 | 2 | 0 |
| Mr. Dave Leggett<br>Air Force Research Laboratory<br>AFRL/VAAI<br>2210 8th Street, Suite 20<br>Bldg 126, Room 301<br>Wright-Patterson AFB OH 45433 | 1 | 0 |
| Dr. Bradley Liebst, Department Head<br>Air Force Institute of Technology<br>Department of Aeronautics & Astronautics<br>Bldg 640 2950 P Street<br>Wright-Patterson AFB OH 45433 | 1 | 0 |

# DISTRIBUTION LIST (Concluded)

| Offsite Distribution | Number of Copies | Number of Electronic |
|---|---|---|
| Mr. Eric Ohmit<br>Calspan Corporation<br>P.O. Box 400<br>Buffalo, NY 14255 | 1 | 0 |
| Mr. David Mitchell<br>Hoh Aeronautics Inc.<br>2075 Palos Verdes Dr. N.<br>Suite 217<br>Lomita, CA 90717 | 1 | 0 |
| Capt Darren Kraabel<br>46th Operations Group, Det 0001<br>Hurlburt Field, FL 32544 | 2 | 0 |
| Capt Eric Fick<br>46th Operations Group<br>Eglin AFB FL 32544 | 2 | 0 |
| LCDR Matt LeTourneau<br>Air Test & Eval Sqdn 9 Det<br>Naval Air Weapons Station<br>Point Mugu, CA 93042-5033 | 1 | 0 |
| Flt Lt Terry Parker<br>Fast Jet Test Squadron<br>Boscombe Downe<br>Salisbury Wiltshire SP40JF<br>United Kingdom | 1 | 0 |
| Ralph H. Smith<br>High Plains Engineering<br>PO Box N<br>Mojave, CA 93502 | 1 | 0 |
| | 26 | 2 |